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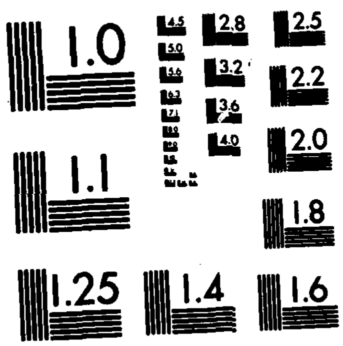

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A two-dimensional, laterally-averaged reservoir hydrodynamic model, LARM, was modified to provide several enhancements. The two major enhancements made to the numerical model were the incorporation of a water quality transport module (WQTM) and the capability to add or delete upstream longitudinal segments during flooding or drawdown. WQTM is a general-purpose transport algorithm for which the user must specify the water quality constituent with sources and sinks and the associated reaction rates.

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20. ABSTRACT (Continued).

This user's guide contains an overall view of LARM2, a summary of its theoretical basis, a description of its application procedure, and an example. The appendices contain an input data description with examples and user notes for two auxiliary codes.

In addition to this guide, there is a more detailed description of the modified model entitled "Developments in LARM2: A Longitudinal-Vertical, Time-Varying Hydrodynamic Reservoir Model" (Edinger and Buchak 1983).

PREFACE

The study reported herein was sponsored by the Office, Chief of Engineers, U. S. Army, as part of the Civil Works General Investigations, Environmental and Water Quality Operational Studies (EWQOS) Program. Work Unit No. 31593 (Task IA.4) entitled "Improve and Verify Multidimensional Hydrodynamic Mathematical Models for Reservoirs" supported the subject study.

The study was conducted during the period July 1978 to October 1980 by Dr. John E. Edinger and Mr. Edward M. Buchak of J. E. Edinger Associates, Inc. Mr. Mark S. Dortch and Dr. Billy H. Johnson of the Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), monitored the effort. This report was written by Mr. Buchak and Dr. Edinger. Program manager of EWQOS was Dr. Jerome L. Mahloch, WES Environmental Laboratory.

Commanders and Directors of WES during this study and the preparation of this report were COL John L. Cannon, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. Fred R. Brown.

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USER GUIDE FOR LARM2: A LONGITUDINAL-VERTICAL, TIME-VARYING HYDRODYNAMIC RESERVOIR MODEL

1. INTRODUCTION

This report is the user guide for a code that permits time-varying hydrodynamic and transport simulations of rivers, lakes, and impoundments. The code is called LARM2, an acronym for laterally-averaged reservoir model, version two. The original LARM was developed for the U. S. Army Engineer Division, Ohio River. Three reports describing its development have been written, the final one of which summarizes the mathematical basis of the code. That report, A Hydrodynamic, Two-Dimensional Reservoir Model: Development and Test Application to Sutton Reservoir Elk River, West Virginia (Edinger and Buchak, 1979), also includes a discussion of the code's first application, with a comparison of model results and prototype data.

Since that time, a dozen or more applications of LARM have been made and additional development work has been funded by U. S. Army Engineer Waterways Experiment Station. The newer version of the code, LARM2, incorporates features that simplify its use and expand its capabilities. Among these are

- additional coding to permit transport computations for water quality constituents beyond temperature;
- the ability to expand and contract the finite difference grid in both the vertical and longitudinal directions as reservoir volume changes in response to flood events and drawdown;
- a decrease of 30% in central processor time requirements

as a result of programming improvements to accommodate vector-processing central processors;

- reduction of application-related code changes to modify a subroutine for the input of time-varying boundary condition data and specify constituent reaction rates;

- the development of a preprocessor code, GIN, to prepare LARM2 geometric data from the output of the Hydrologic Engineering Center program GEDA (Hydrologic Engineering Center, 1976); and

- the development of a postprocessor code, VV, to plot velocity vectors using LARM2 output.

This user guide contains an overall view of LARM2 (Chapter 2), a summary of its theoretical basis (Chapter 3), and an example problem (Chapter 4). A thorough understanding of the example as well as the input data description (Appendix A) is required of the user who is preparing an application.

2. CAPABILITIES AND LIMITATIONS

LARM2 was developed to assist in the analysis of water quality problems in rivers, lakes, and reservoirs where buoyancy is important and where lateral homogeneity can be assumed. The code is recommended for those cases where longitudinal and vertical temperature or constituent gradients occur. LARM2 generates time-varying velocity, temperature, and water quality constituent fields and surface elevations on a longitudinal and vertical grid. Both the spatial and temporal resolution can be varied by the user, within certain limits. Units used are the International System of Units (SI); i.e., metre-kilogram-second.

An application requires a considerable effort in planning and data assembly and computer resources. The user is required to modify a subroutine that supplies time-varying boundary condition data to LARM2 for his particular case. If the user intends to make use of the constituent transport computation option, he must be able to quantify the reaction rates for each constituent in terms of every other constituent and code these statements. The user must also be able to review results for reasonableness and applicability to his problem.

LARM2 in its present form can be applied to a single, continuous reach of a river, lake, or reservoir. Other configurations are possible, such as carrying the computations into branches and tributaries, if the code is employed as a subroutine for each reach and boundary conditions between reaches are specified. This configuration has not been tested, however, and would require significant additional programming.

The code automatically increases the number of horizontal layers when water surface elevations increase and then adds segments as backwaters progress into the upstream end of a reservoir. Similarly, the grid contracts both vertically and longitudinally during drawdown.

Waterbody simulations through long periods are economically feasible. An eight-month simulation at a time step of 15 minutes for temperature and one other constituent on a grid that is 30 segments by 20 layers with 375 active cells would cost $300 on a commerical batch-processing computer system. Each additional constituent would add approximately $30 to this cost. These cost estimates are exclusive of any intermediate simulations and postprocessing of results. Experience has shown that the former may account for ten simulations for each final simulation obtained.

LARM2 has a simple algorithm for the computation of ice formation and breakup that does not explicitly account for the latent heat content of the ice. Typical LARM2 simulations will begin in March and continue through October for a temperate zone waterbody. With care in evaluating computed ice cover, these simulations may be extended to the November-to-February period.

LARM and LARM2 have been tested against analytic solutions and have been applied to a dozen or more field cases. A list of reports describing these applications is given in Appendix H.

3. THEORETICAL BASIS

Details of the formulation of the governing partial differential equations and the subsequent casting of those equations into finite difference form are presented in Edinger and Buchak, 1979. Briefly, six equations (longitudinal momentum, vertical momentum, continuity, heat and constituent balances, and state) are solved to obtain longitudinal and vertical velocity components, surface elevations, temperatures, constituent concentrations, and densities at a grid of points in space and time. The three-dimensional, time-varying partial differential equations are formally averaged over the reservoir width and then cast into finite difference form after vertical averaging over a horizontal layer thickness, h, with boundaries at z=k+½ and z=k-½. The laterally averaged equations as vertically integrated over the layer thickness are presented below:

<u>longitudinal (x-direction) momentum</u>

$$\frac{\partial}{\partial t}(UBh) + \frac{\partial}{\partial x}(U^2Bh) + (u_b w_b b)_{k+\frac{1}{2}} - (u_b w_b b)_{k-\frac{1}{2}}$$

$$+ \frac{1}{\rho}\frac{\partial}{\partial x}(PBh) - A_x \frac{\partial^2}{\partial x^2}(UBh) + (\tau_z b)_{k+\frac{1}{2}} - (\tau_z b)_{k-\frac{1}{2}} = 0 \qquad \text{(1a)}$$

with

$$\tau_z = C^* \rho_a/\rho \; W_a^{\;2} \cos\phi \qquad \text{(surface)} \qquad \text{(1b)}$$

$$= -A_z \, \partial U/\partial z \qquad \text{(interlayer)} \qquad \text{(1c)}$$

$$= g\, U|U|/c^2 \qquad \text{(bottom)} \qquad \text{(1d)}$$

<u>continuity</u>

$$(w_b b)_{k-\frac{1}{2}} = (w_b b)_{k+\frac{1}{2}} + \frac{\partial}{\partial x} (UBh) - \frac{\partial Q}{\partial x} \qquad \text{(internal)} \qquad (2a)$$

$$\frac{\partial (Zb)}{\partial t} - \frac{\partial}{\partial x} \int_H (UB)\,dz + \frac{\partial Q}{\partial x} = 0 \qquad \text{(over total depth)} \qquad (2b)$$

<u>vertical (z-direction) momentum</u>

$$\frac{\partial P}{\partial z} = \rho g \qquad (3)$$

<u>heat balance</u>

$$\frac{\partial}{\partial t} (BhT) + \frac{\partial}{\partial x} (UBhT) + (w_b bT)_{k+\frac{1}{2}} - (w_b bT)_{k-\frac{1}{2}}$$

$$- \frac{\partial}{\partial x} (D_x \frac{\partial BhT}{\partial x}) - (D_z \frac{\partial BT}{\partial z})_{k+\frac{1}{2}} + (D_z \frac{\partial BT}{\partial z})_{k-\frac{1}{2}} = \frac{H_n\ Bh}{V} \qquad (4)$$

<u>constituent balance</u>

$$\frac{\partial}{\partial t} (BhC) + \frac{\partial}{\partial x} (UBhC) + (w_b bC)_{k+\frac{1}{2}} - (w_b bC)_{k-\frac{1}{2}}$$

$$- \frac{\partial}{\partial x} (D_x \frac{\partial BhC}{\partial x}) - (D_z \frac{\partial BC}{\partial z})_{k+\frac{1}{2}} + (D_z \frac{\partial BC}{\partial z})_{k-\frac{1}{2}} = \frac{H_n\ Bh}{V} \qquad (5)$$

<u>state</u>

$$\rho = 5.29157 \times 10^{-5}\ T^3 - 8.45123 \times 10^{-3}\ T^2$$

$$+ 6.59583 \times 10^{-2}\ T + 999.841 \qquad (6)$$

where

A_x	x-direction momentum dispersion coefficient (m^2/s)
A_z	z-direction momentum dispersion coefficient (m^2/s)
b	lake width (m)
B	laterally averaged lake width integrated over h (m)
c	Chezy resistance coefficient, $m^{\frac{1}{2}}/s$
C	laterally averaged constituent concentration integrated over h ($mg \cdot l^{-1}$)
C*	resistance coefficient
D_x	x-direction temperature and constituent dispersion coefficient (m^2/s)
D_z	z-direction temperature and constituent dispersion coefficient (m^2/s)
g	acceleration due to gravity (m/s^2)
h	horizontal layer thickness (m)
H	total depth (m)
H_n	source strength for heat balance ($^{\circ}C \cdot m^3 \cdot s^{-1}$) or constituent balance ($mg \cdot l^{-1} \cdot m^3 \cdot s^{-1}$)
k	integer layer number, positive downward
P	pressure ($Pa = N/m^2$)
Q	tributary inflow and withdrawal rates (m^3/s)
t	time (s)
T	laterally averaged temperature integrated over h ($^{\circ}C$)
U	x-direction, laterally averaged velocity integrated over h (m/s)
u_b	x-direction, laterally averaged velocity (m/s)
V	cell volume ($B \cdot h \cdot \Delta x$) (m^3).
W_a	wind speed (m/s)
w_b	z-direction, laterally averaged velocity (m/s)

x and z	Cartesian coordinates: x is along the lake centerline at the water surface, positive to the right, and z is positive downward from the x-axis (m)
Z	surface elevation (m)
ρ	density (kg/m^3)
ρ_a	air density (kg/m^3)
τ_z	z-direction shear stress (m^2/s^2)
ϕ	wind direction (rad)

The finite difference operation is applied to Equations 1 through 5 and introduces two additional variables, Δx, the x-direction spatial step (m), and Δt, the computation time step (s). This operation produces finite difference equation analogues of Equations 1 through 5. The solution technique is to substitute the forward time, longitudinal momentum term from Equation 1a into the vertically integrated continuity expression, Equation 2b, to give the free surface frictionally and inertially damped longwave equation. The latter is solved implicitly for the surface elevation, Z, which eliminates the longwave speed time step restriction ($\Delta x/\Delta t > \sqrt{gH}$). However, the computation time step, Δt, is still limited by the fundamental condition that

$$\Delta t < V/Q^* \tag{7}$$

for each cell where Q* is the flow into or out of the cell and V is the cell volume.

The computation proceeds as follows. New water surface elevations are computed using the implicit equation combination, Equations 1a and 2b. New longitudinal velocities on the grid are then computed from the explicit Equation 1a. Equation 2a is used to compute vertical velocities, and Equation 2b is used to check water balances prior to the implicit solution of Equations 4 and 5 for temperature and constituent concentrations. Finally, densities are computed from Equation 6*. Results may then be printed and a new time step computation begins once again with the solution for water surface elevation.

The FORTRAN names of the variables introduced in Equations 1 through 5 are given below**:

variable	FORTRAN name	variable	FORTRAN name
A_x	AX	Q	QTRIB, QWD
A_z	AZ	T	T1, T2
B	B	U	U
c	CHZY	V	VOL
C	C1, C2	W_a	WA
C*	CZ	w_b	W
D_x	DX	Z	Z1, Z2
D_z	DZ	Δt	DLT
g	G	Δx	DLX
h	HIN, H1, H2	ρ	RHO
H_n	HN	ρ_a	RHOA
k	K	τ_z	ST
P	P	ϕ	PHI

* Personal Communication, August 1974, Alan Toblin, NUS Corporation, Rockville, Md.

** A glossary of the FORTRAN variables discussed in this report is presented in Appendix E.

The location of the variables on the finite difference grid is important in understanding the FORTRAN coding of LARM2 and the output. Figure 1 shows the location of velocities and dispersion coefficients at cell boundaries. This convention permits boundary values of these variables to be exactly zero. Other variables are located at the cell center and represent averages for the entire cell.

Throughout the computation new values of variables replace old values. The solution technique requires that values of Z, H, T, and C be retained for two time steps. At the end of a time step, the contents of these variable arrays are exchanged so that the older values are placed in arrays with a "1" suffix and the newer values are placed in arrays with an "2" suffix.

4. APPLICATION PROCEDURE AND EXAMPLE

Applying LARM2 to a particular case requires five steps: (1) assembling the necessary data; (2) schematizing the reservoir geometry; (3) modifying a subroutine for the input of time-varying boundary condition data; (4) setting hydraulic and other parameters and constituent reaction rates; and (5) executing the code and evaluating the results. These steps are described below.

4.1 Required Data

The initial task in applying LARM2 to a specific case (after deciding that the problem requires a two-dimensional, time-varying simulation for its solution) is assembling the necessary data. Reservoir geometry is of immediate usefulness and should include bathymetric cross-sections (y-z plane). A plan (x-y plane), an elevation (x-z plane), and an elevation-area-volume table are useful, but not necessary, adjunct information. These data will be used to construct the computational grid.

Initial and boundary condition data are required. The former consists of an initial water surface elevation and temperature for the starting day of the simulation. Boundary condition data in their most general form consist of time-varying inflow rates and temperatures for the upstream inflow and each significant tributary, time-varying release and withdrawal rates, and time-varying meteorological data for wind shear, evaporation, and surface heat exchange calculations. As LARM2 is now coded, surface heat exchange is computed using equilibrium temperature, the coefficient of surface heat exchange, and solar radiation. These parameters are computed separately from air temperature; dew point temperature; wind speed; and observed solar radiation, percent of possible sunshine, or cloud cover data (Edinger, Brady, and Geyer 1974). In their simplest form, the boundary-condition data are constants. For each water quality constituent to be computed, initial and boundary condition data, as well as reaction rates, are needed. Hydraulic properties--Chezy and dispersion coefficients--and solar radiation absorption and attenuation characteristics are also required.

4.2 Geometric Schematization

The geometric data are organized into a grid like the one shown in Figure 2 for Dillon Reservoir. The basic parameters to be selected in defining the grid are the longitudinal spacing, Δx (m), and the vertical spacing, h (m). These parameters are constant throughout the grid and define two of the three dimensions of each cell. The third dimension, the cell widths, are most easily taken from cross-section drawings and represent an average value for each cell. The vertical columns defined by Δx are called segments, and the horizontal rows defined by h are called layers.

A more sophisticated procedure for obtaining cell widths involves the use of the Hydrologic Engineering Center code GEDA and the preprocessor GIN, the user notes for which are included as Appendix F in this guide. GEDA utilizes cross-sectional data from transects at irregular intervals and produces reservoir widths as a function of elevation at regular intervals. GEDA also computes areas and volumes as functions of elevation. Cross-sectional data may be modified using GEDA procedures in order to fit the elevation-area-volume table to one computed from detailed topography and published in the design report for the reservoir. GEDA allows several Δx's and h's to be tried with only small additional effort. GIN uses GEDA output as input and produces the geometry (BA) cards read by LARM2. GIN also may be manipulated to change the computed elevation-area-volume table to more closely match the given table. GIN produces an active/inactive cell map to allow screening of illegal geometric features.

Implicit in the geometric schematization is the identification of the waterbody center line. This may be defined as the dominant flow path, with its origin at the upstream boundary. The center line may follow a path that coincides with the thalweg. All longitudinal distances are measured along the selected center line.

The choice of Δx and h is important to the success of the simulation. By selecting the ratio $h/\Delta x$ to match the overall reservoir slope, the user will find that the reservoir bottom may be modelled more accurately. While relatively small values of Δx and h permit finer resolution, the resulting large number of grid cells requires more computation and storage. A second consideration in the choice of Δx and h is the basic stability criterion that Δt, the integration time step, be less than the volume of each cell divided by the flow through the cell (Equation 7). This criterion also affects economy by forcing smaller Δt's as cell dimensions are decreased.

In practice, Δt can be changed for a particular simulation, while the geometry established initially remains fixed. Surprises from an implicit choice of Δt can be avoided by anticipating the limiting Δt dictated by the geometry. In most cases, this limiting Δt will occur at tributary or upstream inflows and withdrawals or downstream outflows. Equation 7 can be evaluated using the smallest cell volume and largest anticipated flow at these inflow or outflow segments.

The code automatically expands the grid to accommodate rising and falling water surfaces, so that the selected grid should be large enough to contain the largest anticipated volume. The grid consists of active and inactive cells, the former being those at which velocities, temperatures, and constituent concentrations are computed and the latter being those at which no computations are done. Inactive cells are identified by inputing their widths as zero. The grid must satisfy the following rules:

- it must be at least two active cells deep at every segment;
- it must be at least three active cells long at every layer;

- steps in the waterbody bottom profile are permitted as long as each continuous layer produced is at least three cells long;
- the grid must include a layer of inactive cells at the top and bottom and a segment of inactive cells at the left and right, such that those cells representing the waterbody are surrounded on all sides by a layer or segment of inactive cells; and
- cell widths must not decrease from bottom to top in any segment

Active cells are those that may contain water, even though at various times because of flood events and drawdown they do not. The current boundaries of the computation on the grid are defined by the parameters IL and IMAXM1 in the longitudinal and KT and KMAXM1 in the vertical. The minimum values of the parameters IL and KT are each two, indicating the waterbody is at its maximum volume. As drawdown occurs, KT increases, so that the water surface is located near layer KT. If necessary, LARM2 also decreases IL so that segment I=IL is always at least two cells deep.

Layers are identified by the layer number K, with a range of 1 to KMAX. Each of these has an elevation associated with it, so that

$$EL = h \cdot (KMAX - KT+1) - Z + DTM \tag{8}$$

is the water surface elevation, where DTM is the distance from some reference datum to the bottom of the grid. LARM2 computes water surface elevations in terms of the layer number, K, and the local elevation, Z, rather than an actual elevation. Longitudinal distances are given in terms of the segment number I.

Mapping these segments and layers back onto the plan and elevation of the reservoir will help to relate LARM2 results to specific reservoir locations.

This mapping will also be useful in establishing the locations of inflows and outflows. LARM2 uses the following definitions:

- upstream inflows occur only at I=IL (left boundary) and are defined by the variables QIN, TIN, and CIN;
- downstream outflows occur only at I=IMAXM1 (right boundary) and are defined by the variable QOUT;
- there must always be an inflow and at least one outflow specified, although the associated flows may be zero;
- tributaries can occur in any segment from I=IL to I=IMAXM1; each tributary must have an associated flow, temperature, and constituent concentration; and
- withdrawals can be located in any segment and layer and each must have an associated flow.

The reservoir orientation may be specified if wind speed and direction data are available and if wind stress computations are desired. The general reservoir direction is determined by the angle the center line (x-axis, positive to the right downstream) makes with north.

LARM2 as presently coded will handle grid sizes up to 30 segments long and 50 layers deep. Larger sizes will require dimension statements to be changed. These statements are marked "DIMENS" in columns 73 to 80, and instructions for changing them are located in comment statements preceding each dimension statement. Dimension statements are found in the main program and subroutines TRIDAG, GRIDG, GRID, and GRIDC.

4.3 Time-Varying Boundary Condition Data

In order to model the water and heat budgets accurately through the simulation period, it is necessary to consider both heat exchange at the water surface and mass and heat advected into or out of the waterbody. These parameters are provided to the main code through the subroutine TVDS, which is an acronym for time-varying data selector. This subroutine performs two tasks. It is called once in order to read the time-varying data. On each succeeding call, TVDS receives from the main code the current simulation time and returns to the main code the value of each of the parameters specified in its call. TVDS must be modified by the user to accommodate his particular data. Minimum data requirements are flows and temperatures for the upstream inflow (QIN, TIN) and each tributary (QTRIB, TTRIB); outlet flows at the dam (QOUT) and each withdrawal (QWD); and the heat exchange parameters, CSHE, SRO, and ET. If evaporation is to be computed, the dew point temperature (TD) is required; wind speed (WA) and direction (PHI) are needed for wind stress computations. For each constituent being simulated, inflow and tributary concentrations are also required. These parameters can be supplied at any time interval. Daily or more frequent data is recommended, although in some cases simulations made with constant parameters are useful.

The subroutine TVDS is given the simulation time (variable ELTM) which is measured in Julian days and fractions thereof.

ELTM is computed in LARM2 as TMSTRT + N * DLT/86400, where N is the current iteration number. Note that an ELTM of 1.75 means January 1, 6 p.m. and that an ELTM of 72.0 is midnight March 12/ March 13. A Julian date calendar is given in Appendix I.

In the most general case, TVDS has available from its original call several arrays, each one of which contains time-varying data from a separate disc or tape file. In the example of Dillon Reservoir, one array contains all the flow data, a second array the ammonia concentration data, and a third the preprocessed meteorological data, including an inflow temperature estimate for the upstream inflow and two tributaries. The first two arrays contain daily data, and the last one contains data on an irregular interval. All these files are chronological, which is essential for the TVDS algorithm. Pairs of times associated with each data file are examined sequentially and compared to ELTM, beginning with the previously located line of data. When the correct line is located, the data is extracted from the array and set equal to the proper subroutine arguments. In the example shown, all three data arrays are examined in this manner before the time-varying boundary condition data are returned to the main code. The subroutine also contains error-checking routines.

It is important that the prospective user study the TVDS subroutine. Differences in data availability and format make it easier for the user to tailor TVDS to his data than to attempt to create a generalized TVDS able to handle all cases.

4.4 Initial Conditions, Hydraulic Parameters, and Constituent Reactions

Having established a grid to represent the reservoir and assembled time-varying data for the simulation period, it is then necessary to select initial conditions to start each simulation. These consist of a water surface elevation and temperature corresponding to the simulation starting time. This information is coded on the IC input card (Appendix A). If the water quality constituent computation option is used, initial conditions for each constituent are required. These are specified on the CC card.

The initial temperature (and constituent) field is specified as a single number, so that the code begins with an isothermal field. With some reprogramming, a stratified field can be used. For the usual simulation situation of early spring start-up, the isothermal approach works well. When there is no available data to begin a simulation, this may be the only possible approach. In flow-dominated cases, the computations require an initialization period approximately equal to the reservoir residence time to damp out this initial temperature estimate. Therefore, the initial results up to approximately a residence time into the simulation may be spurious. If this time period is important, it is suggested that the time-varying data be duplicated at the start of the simulation such that, for example, March's meteorological and hydrologic data is followed by March (again), April, May, etc., for a waterbody with a residence time of about a month. This procedure may be continued as additional simulations are made, or results for the end of March may be used to define a new initial elevation and temperature. This technique can also be used to extend a previous simulation by selecting initial conditions from the previous simulation results.

The flow field is always initialized to zero by the code. The solution technique is such that the applied boundary conditions very quickly force an internally compatible flow field.

Hydraulic parameters consist of A_x, A_z, and the Chezy coefficient. These parameters are defined in Chapter 2 of this guide, and suggested values are coded in DATA statements. A_x and A_z may be varied by several orders of magnitude, with the following exception. A_z, the vertical dispersion of momentum coefficient, has limits of the molecular value (1.5×10^{-6} m^2/s) as a minimum and a value related to the horizontal layer thickness and the time step as a maximum ($A_z<h^2/2\Delta t$). The latter limit is derived from the computation time step limit, Equation 7. The value of A_z varies spatially and temporally within these limits and is computed by the code from the Richardson number, which is the local ratio of buoyancy to shear. The value of A_z used in the computation is a function of a base value for this parameter, A_{z0}, and the Richardson number:

$$A_z = A_{z0}\ (1 + 10Ri)^{-1/2} \qquad (9)$$

where Ri is the Richardson number. It is necessary to set only A_{z0}, as the code automatically keeps the value of A_z within the molecular and computational limits. A_x is presently set at a single value that is constant over time and space, but the numerical formulation allows it to vary spatially and temporally with additional coding.

The Chezy coefficient is also space- and time-invariant, but can be made variable with some reprogramming. Boundary friction varies spatially with the amount of side and bottom area exposed, as well as temporally with the flow field. Chezy may be varied by a factor of four from the value given in the LARM2 DATA statement.

The temperature equation dispersion parameters may be varied. These parameters are D_x and D_z, the longitudinal and vertical dispersion coefficients. Like A_x, D_x is temporally and spatially invariant, and its value is controlled by the FORTRAN variable DXI. D_z varies over time and space and is also computed from the Richardson number and a base value, D_{z0}. Like the momentum equation parameter A_z, D_z operates over a range from a minimum molecular value to a computational maximum of $h^2/2\Delta t$.

Finally, the distribution of solar radiation in the vertical is controlled by the parameters β and γ (FORTRAN BETA and GAMMA) as follows:

$$H_s(z) = (1 - \beta) H_s(z=0)^{-\gamma z} \quad (10)$$

where

H_s solar radiation rate at depth z ($^{o}C \cdot m^3 \cdot s^{-1}/m^2$)

β fraction of H_s absorbed at the water surface

γ attenuation rate

Note that these parameters control only the distribution of solar radiation in the vertical and that overall surface heat exchange, including solar radiation, is summarized in the parameters CSHE and ET. If β=1, all the solar radiation is absorbed in the current top layer (K=KT) and the value of γ is arbitrary.

Constituent Reactions

For each constituent specified, constituent reaction rates and internal sources and sinks need to be coded. For the user who desires only hydrodynamic and temperature simulations, this section of the user guide may be skipped. For a detailed description of the constituent transport computations, the user is referred to "Developments in LARM2: A Longitudinal—Vertical, Time—Varying Hydrodynamic Reservoir Model " (Edinger and Buchak, 1983).

The variable RR(JC,M) is the rate at which constituent JC is transferred to constituent M and may be dependent on a number of spatially and temporally varying variables, such as temperature. For the case of M=JC, RR is negative and is the linear decay rate. RR has the units of s^{-1}.

The variable HN(I,K) is the spatially and temporally varying source and sink term for constituent JC. HN(I,K) has the units mg $l^{-1} \cdot m^3 \cdot s^{-1}$. The user is required to augment this array by the amount of material added to or subtracted from constituent JC due to the reactions specified by RR.

The user must examine DO loop 1840 in the LARM2 code and modify it to compute RR and HN as required for his constituents. The user may also specify different sources and sinks in the surface or bottom layers by separate statements for layers K=KT or K=KB. The computation for each constituent concentration (DO loop 1820) begins with an initialization of the HN array. Then, for each location I,K, the reaction rate (RR) array is computed, one FORTRAN statement for each constituent pair JC,M. HN is then augmented by the rate at which constituent JC is transferred to or from constituent M. The remainder of the computation requires no user changes and includes the augmenting of HN by external sources and sinks, the retrieving of the transport coefficient vectors, and the call to the subroutine TRIDAG for layer-by-layer solution of the transport equation.

4.5 Input, Output and Computer Resource Requirements

The input data stream is described in Appendix A, and an example data set for Dillon Reservoir is given in Appendix B. LARM2 output for this data set is given in Appendix C. The output shown there is for IFORM=0, that is, compressed (for 80-character-width printers) and shortened results. The normal form of the output (for 132-character-width printers) can be obtained by setting the parameter IFORM=1. Although an example of this more complete output is not given, the user may quickly make his own by changing the IFORM parameter (PR card, field 1) from 0 to 1. The additional information generated by the longer output is as follows:

- the long form produces three geometry tables: a grid showing active and inactive cells, a grid showing cell widths as augmented by LARM2 (widths assigned to inactive cells), and an elevation-area-volume table;
- the initial conditions for Z2, U, W, and T2 (and C2): the velocity fields are always initialized to zero at the start of the computation, Z2 and T2 are initialized through the IC card;
- eight additional segment results for Z2, V, W, and T2 (and C2), using the additional columns available on 11-inch by 14-inch paper.

A second type of output is available from the LARM2 code, and it is useful in postprocessing applications such as the vector plotting code VV. Cell coordinate positions are written unformatted to TAPE61, followed by U and W fields at times selected on the PL card (see Appendix A). This information is used by VV to plot displacement vectors on a scaled grid.

However, by saving additional information on TAPE61, time series plots of other variables may be obtained, as well as statistical analyses of, for example, outflow temperatures or velocity records at a particular reservoir location.

The code and test data as supplied requires 254,000 octal words of storage on a Controlled Data Corporation (CDC) 175. This storage requirement depends on both the grid size and the amount of time-varying boundary condition data stored. LARM2 requires 0.00026 s of central processor (cpu) time for each time step iteration for each active cell at a high level of compiler optimization. The Dillon Reservoir example uses 90.84 s of cpu time for its 366 active cells for a simulation of 960 steps, plus 9.5 s for compilation.

4.6 Dillon Reservoir Example

Dillon Reservoir is located in Colorado approximately 90 km west of Denver in the Rocky Mountains. The reservoir is used for water supply as well as for receiving effluent from a wastewater reclamation facility serving nearby ski resorts. The problem addressed with the LARM2 simulations is the dilution and decay of ammonia from the treatment plant located on a tributary and from nonpoint sources in the basin. The vertical and longitudinal distribution of ammonia in the reservoir arms is of particular interest since several species of fish migrate through the arms to the shallow tributaries to spawn. The unusual geometry and the inclusion of constituent computation make this a complex case. However, the user will find elements of many applications in the Dillon Reservoir example and is encouraged to study it.

Figure 3 shows Dillon Reservoir in plan. In order to include both the Blue River and Tenmile Creek arms in the LARM2 grid, the center line was drawn as shown in Figure 4. Cross-sectional data at 500-ft intervals were obtained and formatted for GEDA. The results of the GEDA run were satisfactory with regard to the comparison of the design report elevation-area-volume table, so GIN was run with the GEDA results as input. Several GIN runs were required to produce an acceptable geometry; some modification of the widths was necessary to match the top layer surface area with the design report surface area and produce a good volume fit elsewhere in the vertical. The final GIN run provided the BA cards for use as LARM2 input (Appendix B). The final grid is shown in Figures 2 and 4. The output from GIN also gives the information required on the GE input card, namely the grid size, Δx and h, and the elevation of the grid relative to the reference datum.

Coincident with establishing a grid representation of Dillon Reservoir, inflows and withdrawals and inflow temperatures and ammonia concentrations were identified. For the grid shown in Figure 2, the following nomenclature was adopted:

Blue River:	QIN, TIN, CIN(1) - upstream inflow
Snake River:	QTRIB(1), TTRIB(1), CTRIB(1,1) - segment 9
Tenmile Creek:	QTRIB(2), TTRIB(2), CTRIB(2,1) - segment 17
Roberts Tunnel:	QWD(1) - segment 9, layer 28
Dam:	QWD(2) - segment 10, layer 35

Note that because of the bending of the center line up the Tenmile Creek arm, the dam outflow is now taken as a withdrawal, not an outlet as defined for LARM2. The code requires at least one outlet, so one is specified (on the OU card), but its flow is always set to zero in TVDS and its layer specification on the OU card is arbitrary. Also note that the inflow as defined for LARM2 is the Blue River and that Tenmile Creek is treated as a tributary, that is, it is not considered a momentum source for the reservoir. The assignment of these inflows and withdrawals allows completion of the TR, TL, WD, WI, and WK cards.

The time-varying data were made available in three files for flows, inflow ammonia concentrations, and meteorological data. The meteorological data were preprocessed from a record consisting of date and time, air and dew point temperatures, wind speed and direction, and observed cloud cover to a record consisting of year, Julian date, dew point temperature, wind speed and direction, equilibrium temperature, coefficient of surface heat exchange, estimated solar radiation, and response temperature. Response temperature is computed as

$$D \frac{dTr}{dt} = k \left(T_r - E\right) \tag{11}$$

where

D	assumed depth (m)
T_r	response temperature (^{o}C)
t	time (s)
k	kinematic coefficient of surface heat exchange (m/s)
E	equilibrium temperature (^{o}C)

The response temperature was used to estimate TIN, TTRIB(1), and TTRIB(2) because inflow temperature records were not available. Equation 11 represents a heat balance for a fully-mixed condition in which change in heat storage is balanced by surface heat exchange. By adjusting the depth, D, to fit the few available observations, an estimate of the seasonal inflow temperature was made.

The subroutine TVDS was constructed around the three time-varying data files. On LARM2's first call to TVDS each of the three files is read, converted to SI units, and stored in arrays. On every other call to TVDS, the arrays are searched to locate the time-varying data corresponding to the LARM2 time variable ELTM. Since the data files are sequential, the lower-loop parameter can be updated every time the correct data is located. This updating permits the next search to begin at the previous successful location.

Observed data for the 1975 study year consisted of daily water surface elevations and weekly temperature profiles at a single location. Initial conditions for each simulation were selected from these data. The first simulations were for a few days only and were checked for correct time-varying data and reasonableness of results. Long-term simulations were then made beginning with January 2 and continuing throughout the year. It was found that a Δt of 900 s was too large to accommodate the velocities of the fall turnover, so that a Δt of 600 s was used thereafter for each long-term simulation. The results of long-term simulations were compared to the weekly temperature observations. These comparisons showed the LARM2 computed temperatures too high in the spring and too low in the fall. A heat budget analysis showed that the error was due to inflow temperatures that responded too quickly to the annual heating-cooling cycle due to meteorological conditions. By increasing the parameter D in Equation 11, a better inflow temperature estimate was obtained. The LARM2 simulations using this new record produced satisfactory agreement between computed and observed temperatures within the limits of extrapolating meteorological data from a distant site.

Weekly velocity plots were also examined using the post-processor VV. Although no current measurements were available for Dillon Reservoir, the plots were studied for overflow, interflow, and underflow in the reservoir arms as well as for behavior during turnover.

Once the computed velocity and temperature fields were shown to be realistic, ammonia simulations were begun. Once again, data from the observation record were used for initial conditions and verification. The first simulations proved to be satisfactory. Finally, new inflow ammonia concentrations, reflecting an expected increase in treatment plant loading, were substituted for the existing ammonia concentration file. The results of this simulation were examined for effects on the fish community with regard to potentially toxic levels and possible interference with spawning activities.

The time-varying data files given in the test data set and shown in Appendix B are for two weeks of the 1975 complete data set. The example simulation shown in Appendix C used results from the full-year simulation to obtain initial conditions. For the two weeks of data shown, a Δt of 900 s proved to be acceptable.

REFERENCES

Edinger, J.E., Brady, D.K., and Geyer, J.C. (1974), Heat Exchange and Transport in the Environment, Publication No. 74-049-00-3, Electric Power Research Institute, Palo Alto, Calif.

Edinger, John Eric and Edward M. Buchak (1979), A Hydrodynamic, Two-Dimensional Reservoir Model: Development and Test Application to Sutton Reservoir Elk River, West Virginia, Contract No. DACW27-76-C-0089 , U. S. Army Engineer Division, Ohio River, Cincinnati.

Edinger, John Eric and Edward M. Buchak (1983), Developments in LARM2: A Longitudinal-Vertical, Time-Varying Hydrodynamic Reservoir Model, Technical Report in press, prepared by J. E. Edinger Associates for U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Hydrologic Engineering Center (1976), Geometric Elements from Cross Section Coordinates, Davis, Calif.

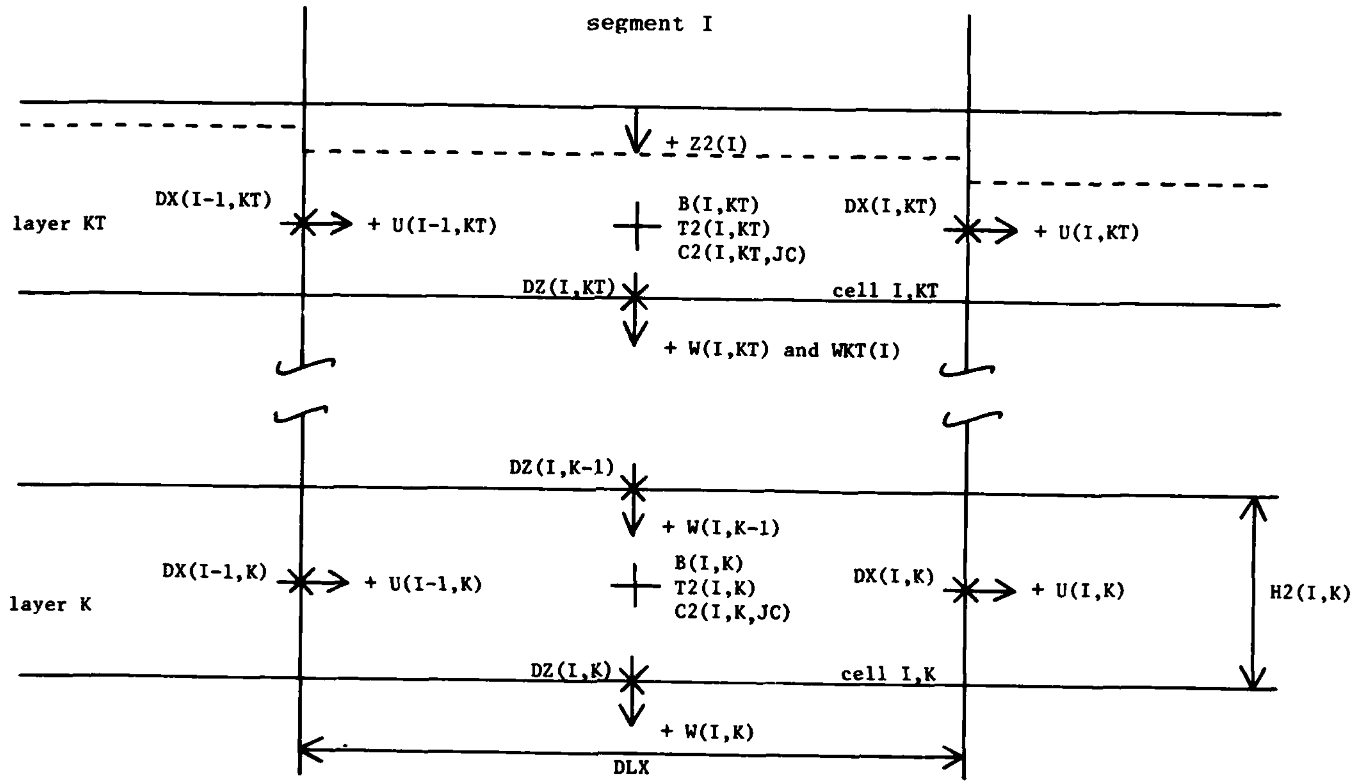

FIGURE 1 Locations and Sign Conventions of Major FORTRAN Variables on Finite Difference Grid

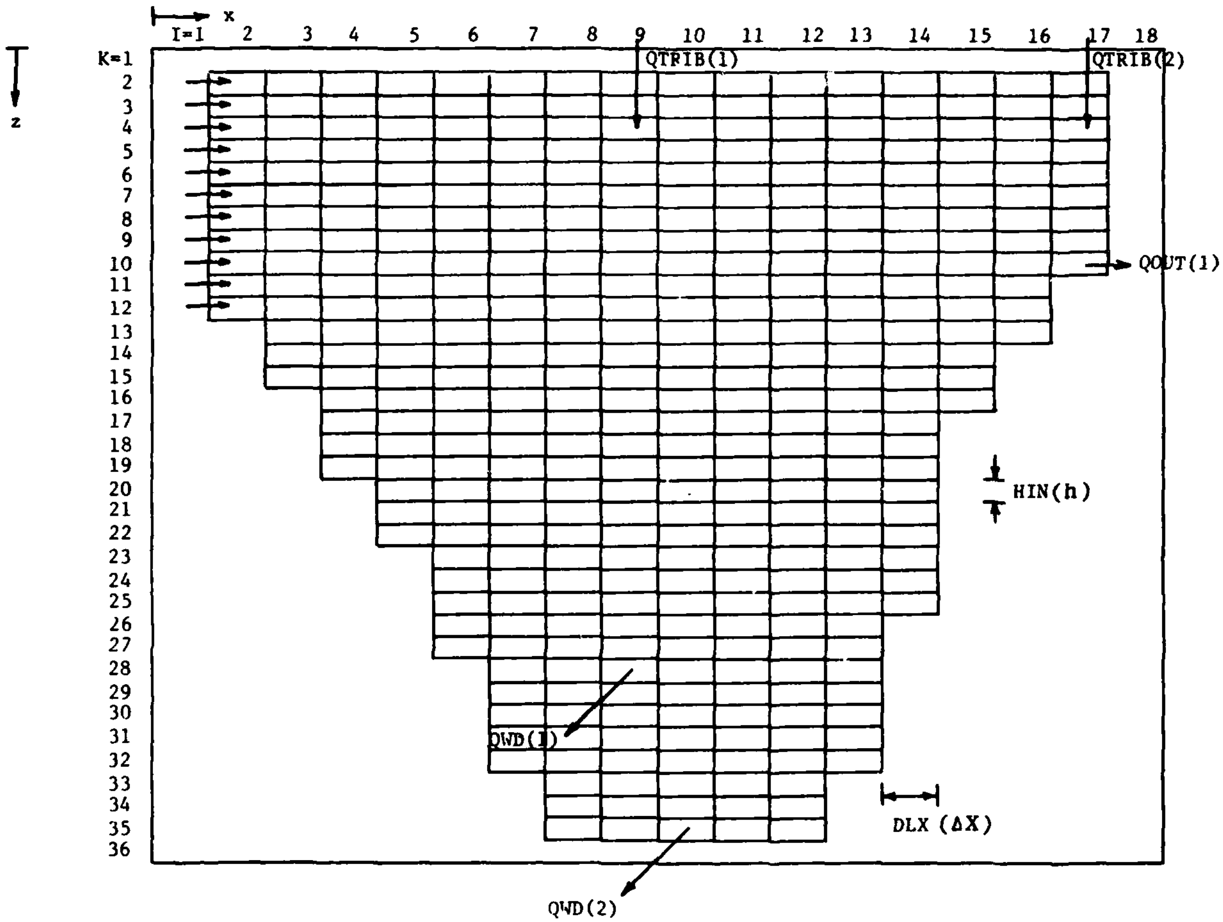

FIGURE 2 Dillon Reservoir Finite Difference Grid

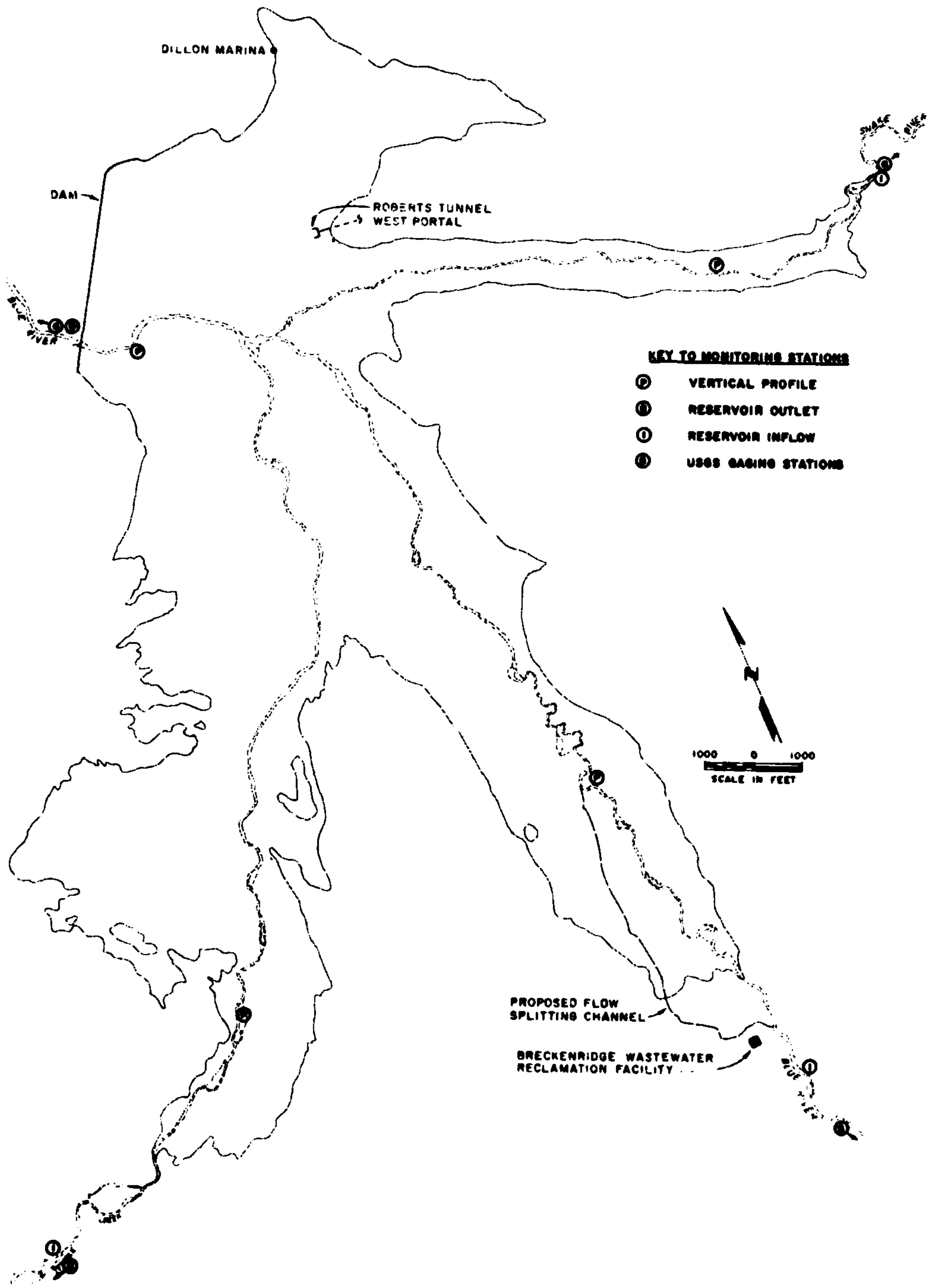

FIGURE 3 Dillon Reservoir

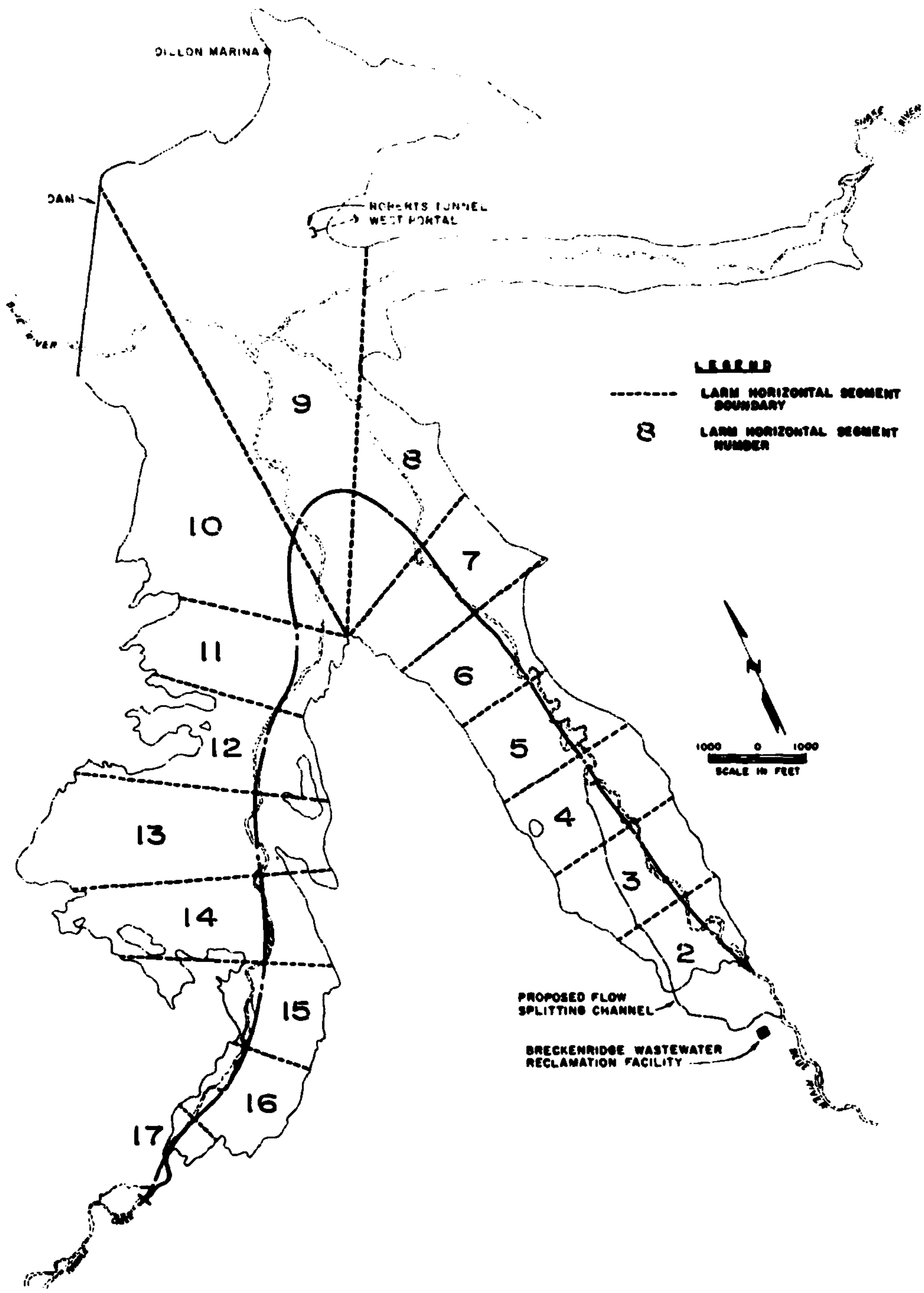

FIGURE 4 Dillon Reservoir LARM Segmentation

Appendix A

LARM2 Input Data Description

GENERAL

Descriptions for each of the cards (or card images) used as input to LARM2 are presented on the following pages. There are three data types:

alphanumeric;

real (may be left or right justified); and,

integer (must be right justified).

There are eleven data fields per card:

Field	Length	Columns
0	2	1-2
1	6	3-8
2	8	9-16
3	8	17-24
4	8	25-32
5	8	33-40
6	8	41-48
7	8	49-56
8	8	57-64
9	8	65-72
10	8	73-80

This format is similar to that used in the Hydrologic Engineering Center codes.

TITLE CARDS (REQUIRED)

Title cards may be used to identify applications, simulations or other parameters as required. These cards do not otherwise affect the computation.

CARD T1

The text input with this card appears in the header with each velocity, temperature, and constituent field snapshot, as well as in the overall header printed once for each simulation.

Field	Parameter	Value	Description
0	AID	T1	alphanumeric: card identification
1-9	TITLE(1,J), J=1,7		alphanumeric: simulation identification text

CARD T2

The text input using this card always appears in the overall simulation header and appears in the first snapshot header if IFORM=1.

Field	Parameter	Value	Description
0	AID	T2	alphanumeric: card identification
1-9	TITLE(2,J), J=1,7		alphanumeric: simulation identification text

CARD T3

The text input using this card always appears in the overall simulation header and appears in the first snapshot header if IFORM=1.

Field	Parameter	Value	Description
0	AID	T3	alphanumeric: card identification
1-9	TITLE(3,J), J=1,7		alphanumeric: simulation identification text

A4

CARD T4

The text input using this card always appears in the overall simulation header and appears in the first snapshot header if IFORM=1.

Field	Parameter	Value	Description
0	AID	T4	alphanumeric: card identification
1-9	TITLE(4,J), J=1,7		alphanumeric: simulation identification text

Note: The variable TITLE is dimensioned to accommodate seven ten-character words per line, which is characteristic of CDC processors. The number of characters per word varies: IBM accommodates four, Univac six. In adapting LARM2 to other machines, both the dimension of TITLE and FORMAT statements 500, 610, 615, 764, 765, and 9000 may need to be changed.

GEOMETRY CARD (REQUIRED)

CARD GE

The geometry card specifies the grid size (number of segments and layers), the length and height of the individual cells, and the location of the grid relative to a reference datum.

Field	Parameter	Value	Description
0	AID	GE	alphanumeric: card identification
1	IMAX	≥ 5	integer: number of segments
2	KMAX	≥ 4	integer: number of layers
3	DLX	+	real: Δx, cell length, m
4	HIN(1,1)	+	real: h, cell height, m
5	DTM	-,0,+	real: distance from reference datum to lower grid boundary, m

Note: LARM2 requires a grid with IMAX$\geq$5 and KMAX$\geq$4. A typical grid has IMAX in the 10-to-30 range, KMAX in the 15-to-50 range. Grid sizes larger than 30×50 require changing the code's dimension statements. Instructions for doing so are given in comment cards preceding each dimension statement, each of which is marked "DIMENS" in columns 73-80.

Typical cell sizes are DLX in the 0.5-km-to-10-km range and HIN(1,1) in the 0.5-m-to-3-m range.

TIME CARD (REQUIRED)

CARD TM

This card determines the simulation length by specifying the temporal iteration size and the number of iterations.

Field	Parameter	Value	Description
0	AID	TM	alphanumeric: card identification
1	DLT	+	real: Δt computation time step, s
2	NSTEPS	+	integer: number of iterations

Note: The simulation length is NSTEPS * DLT, in seconds.

PLOT CARD (REQUIRED)

CARD PL

This card specifies whether, and at what frequency, velocity fields are saved for postprocessing by VV, the vector plotting code.

Field	Parameter	Value	Description
0	AID	PL	alphanumeric: card identification
1	IPLOT	0	integer: no information saved
		1	integer: information saved
2	M1	0,+	integer: information is saved beginning at iteration M1; if IPLOT=0, this paramter has no effect
3	M2	0,+	integer: information is saved every M2 iterations; if IPLOT=0, this parameter has no effect

Note: If IPLOT=1, M1=960, and M2=96 for example, postprocessing information is saved every 96 iterations, beginning at iteration 960.

PRINT CARD (REQUIRED)

CARD PR

This card specifies the form of the printed output, as well as the frequency of the velocity, temperature, and constituent field snapshots.

Field	Parameter	Value	Description
0	AID	PR	alphanumeric: card identification
1	IFORM	0	integer: output shortened (cell widths and volume-area-elevation table suppressed) and compressed to fit an 8½-inch page width
		1	integer: normal output using entire 132-column page width (14 inches)
2	N1	0,+	integer: snapshots are printed beginning at iteration N1
3	N2	0,+	integer: snapshots are printed every N2 iterations

Note: The parameters N1 and N2 are used like the parameters M1 and M2 on the PL card. The segments for which elevations, velocities, and temperatures are printed in the snapshots are specified on the I0, I1, and I2 cards.

SEGMENT PRINT SELECTOR CARDS (REQUIRED)

These cards permit the user to select which segment results are to be printed for IFORM=0 and IFORM=1. Nine segments may be selected for IFORM=0 (short form) and 17 segments for IFORM=1 (long form).

CARD I0

Field	Parameter	Value	Description
0	AID	I0	alphanumeric: card identification
1-9	I0(I), I=1,9	$1 \le I0 \le IMAX$	integer: segment number

CARD I1

Field	Parameter	Value	Description
0	AID	I1	alphanumeric: card identification
1-10	I1(I), I=1,10	$1 \le I1 \le IMAX$	integer: segment number

CARD I2

Field	Parameter	Value	Description
0	AID	I2	alphanumeric: card identification
1-7	I1(I), I=11,17	$1 \le I1 \le IMAX$	integer: segment number

Note: If IMAX<9 or IMAX<17, segment numbers may be repeated to complete the card requirements.

INITIAL CONDITION CARD (REQUIRED)

CARD IC

This card defines the starting time in Julian days and the corresponding initial water surface elevation and temperature.

Field	Parameter	Value	Description
0	AID	IC	alphanumeric: card identification
1	TMSTRT	$0 \leq TMSTRT \leq 366$	real: simulation starting time, Julian days
2	KT	$KMAX-2 \leq KT \leq 2$	integer: layer number for initial water surface elevation
3	ZI	$-0.8*HIN(1,1) \leq ZI \leq 0.25*HIN(1,1)$	real: initial water surface elevation relative to layer KT, m (positive down)
4	TI	$0 \leq TI \leq 100$	real: initial temperature, ^{o}C

Note: KT and ZI give the water surface elevation and TI the temperature corresponding to the time TMSTRT. Values of 3 for KT and 0.1 m for ZI, for example, place the initial water surface elevation 0.1 m below the top of layer 3. The initial temperature field is isothermal at TI. The simulation begins at TMSTRT and ends at TMSTRT + NSTEPS * DLT/86400, in days.

CONSTITUENT DEFINITION CARD (REQUIRED)

CARD CD

This card specifies the number of water quality constituents to be simulated and also permits these transport computations to be turned off for a particular simulation.

Field	Parameter	Value	Description
0	AID	CD	alphanumeric: card identification
1	NC	$0 \leq NC \leq 10$	integer: number of constituents to be simulated; if NC>0, the following card, CONSTITUENT INITIAL CONCENTRATION CARD, is required
2	ICC	0	integer: constituent transport computations suppressed
		1	integer: constituent transport computations performed

Note: The user generally will complete a hydrodynamic and temperature simulation to his satisfaction (ICC=0) before going on to the water quality constituent computations (ICC=1).

Water quality reaction-iteration rates also must be specified for each water quality constituent. Since these rates are usually a function of temperature, they must be computed in LARM2. The location for the user to insert this computation is discussed in Section 4.4 of this guide.

CONSTITUENT INITIAL CONCENTRATION CARD (OPTIONAL)

CARD CC

This card contains the initial concentration for each of the NC constituents and is required if NC>0.

Field	Parameter	Value	Description
0	AID	CC	alphanumeric card identification
1-10	CI(JC) JC=1,NC	$CI(JC)\geq 0$	real: initial concentrations for each of NC constituents

Note: LARM2 initializes the entire reservoir to CI(JC).

METEOROLOGICAL PARAMETER CARD (REQUIRED)

CARD MP

This card specifies the reservoir orientation for wind stress computations and also whether evaporation is included in the water budget computations.

Field	Parameter	Value	Description
0	AID	MP	alphanumeric: card identification
1	PHIO	$0 \leq PHIO < 2\pi$	real: the angle between the positive x-axis (reservoir centerline in the flow direction) and north, rad
2	IEVAP	0	integer: evaporation rates not computed and not included in water budget computations
		1	integer: evaporation rates computed and included in water budget computations

Note: For a reservoir flowing from east to west, PHIO=$\pi/2$; southwest to northeast, PHIO=$5\pi/4$. This convention is similar to the meteorologist's convention for wind direction.

Evaporation rates are sometimes given in the inflow record as QIN_{net}=QIN-QET. This is the case for which IEVAP should be set to 0. The contribution of evaporation to surface heat exchange is always considered, regardless of the value of IEVAP.

OUTLET CARD (REQUIRED)

CARD OU

This card specifies the number of reservoir outlets and their elevations. At least one outlet is required.

Field	Parameter	Value	Description
0	AID	OU	alphanumeric: card identification
1	NOUT	$1 \leq NOUT \leq 9$	integer: number of outlets located at right grid boundary
2-10	KOUT(J), J=1,NOUT	$2 \leq KOUT(J) \leq KMAX-1$	integer: layer number for each outlet

Note: For each outlet specified, a flow needs to be supplied by the subroutine TVDS. At least one outlet is required, although its flow may be set to zero.

A single outlet spanning a number of layers may be specified by breaking the single outlet into several and dividing the outflow among them.

TRIBUTARY CARD (REQUIRED)

CARD TR

This card specifies the number of reservoir tributaries.

Field	Parameter	Value	Description
0	AID	TR	alphanumeric: card identification
1	NTRIB	$0 \le NTRIB \le 10$	integer: number of reservoir tributaries; if NTRIB>0, then the following card, TRIBUTARY LOCATION CARD, is required

Note: For each tributary, an inflow and inflow temperature need to be supplied by the subroutine TVDS.

TRIBUTARY LOCATION CARD (OPTIONAL)

CARD TL

This card gives the reservoir segment numbers at which tributary inflows enter and is required if NTRIB>0.

Field	Parameter	Value	Description
0	AID	TL	alphanumeric: card identification
1-10	ITRIB(J), J=1,NTRIB	$2<\text{ITRIB(J)} \leq \text{IMAX}-1$	integer: segment number at which each tributary enters

Note: Tributary flows are entered in the segment specified here and at a layer that corresponds to their density. Tributaries above the current upstream boundary segment, IL, on any particular time step are combined with the upstream inflow.

WITHDRAWAL CARD (REQUIRED)

CARD WD

This card specifies the number of withdrawals from the reservoir.

Field	Parameter	Value	Description
0	AID	WD	alphanumeric: card identification
1	NWD	$0 \le NWD \le 10$	integer: number of reservoir withdrawals; if NWD>0, then the following cards, WI and WK, are required

Note: For each withdrawal, an outflow rate needs to be supplied by subroutine TVDS.

WITHDRAWAL SEGMENT CARD (OPTIONAL)

CARD WI

This card specifies the longitudinal location (segment) for each withdrawal and is required if NWD>0.

Field	Parameter	Value	Description
0	AID	WI	alphanumeric: card identification
1-10	IWD(J), J=1,NWD	$2 < IWD(J) \leq IMAX-1$	integer: segment number for each of NWD withdrawals

Note: The layer number for each withdrawal is specified on the WK card, which follows.

WITHDRAWAL LAYER CARD (OPTIONAL)

CARD WK

This card specifies the vertical location (layer) for each withdrawal and is required if NWD>0.

Field	Parameter	Value	Description
0	AID	WK	alphanumeric: card identification
1-10	KWD(J), J=1,NWD	$2 < KWD(J) \leq KMAX-1$	integer: layer number for each of NWD withdrawals

Note: The segment number for each withdrawal is specified on the preceding card. Each individual withdrawal must have its segment and layer specified in the same field on the WI and WK cards, respectively.

A single withdrawal spanning a number of layers may be specified by breaking it into several. Withdrawals above the current upstream boundary segment, IL, or above the current water surface layer, KT, are ignored.

BATHYMETRY CARDS (REQUIRED)

CARDS BA

These cards contain the cell widths for each of the IMAX KMAX cells, which are taken from cross-section drawings and represent an average value for each cell. GEDA produces widths as a function of elevation; GIN (see Appendix F) uses GEDA output and produces BA cards used by LARM2.

Field	Parameter	Value	Description
0	AID	BA	alphanumeric: card identification
1-10	B(I,K)	$B(I,K) \geq 0$	real: cell widths, m (left to right, top to bottom, filling each BA card)

Note: For the grid boundary segments (I=1 and I=IMAX) and boundary layers (K=1 and K=KMAX), B must be set to zero; inactive cells also are identified by setting their widths to zero.

The read statement for these cards is READ(5,500) ((B(I,K),K=1,KMAX),I=1,IMAX).

TVDS DATA CARDS (OPTIONAL)

These cards contain the time-varying boundary condition data for the simulation. Since they are read by the user-written subroutine TVDS, no format is specified here. A discussion of the time-varying boundary condition data and TVDS can be found in Section 4.3.

Appendix B

Example Input Data

```
T1USER GUIDE EXAMPLE -- DILLON RESERVOIR, COLORADO -- 2/18/81
T2UPSTREAM INFLOW, TWO TRIBUTARIES, TWO WITHDRAWALS, AND NO OUTFLOW
T3ONE CONSTITUENT (AMMONIA)
T4IFORM=0 FOR SHORTENED AND COMPRESSED OUTPUT
GE      18      36  552.75      2.  2679.3
TM    900.      48
PL       0       0      48
PR       0       0      48
I0       1       2       3       4       5       7       9      12      15
I1       1       2       3       4       5       6       7       8       9      10
I2      11      12      13      14      15      16      17
IC   214.5       3   -1.25    10.5
CD       1       1
CC    0.02
MP     3.9       1
OU       1      10
TR       2
TL       9      17
WD       2
WI       9      10
WK      28      35
BA      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.    881.    727.    551.
BA    399.    286.    183.    112.     67.     37.     19.      8.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
BA      0.      0.      0.   1056.    967.    855.    763.    682.    544.    413.
BA    301.    206.    130.     75.     39.     20.     10.      0.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.      0.      0.   1112.
BA   1068.   1008.    971.    947.    846.    735.    622.    499.    379.    276.
BA    191.    127.     85.     56.     35.     19.      9.      0.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
BA      0.      0.      0.      0.      0.   1081.   1057.   1036.   1036.   1036.
BA    984.    924.    854.    766.    670.    571.    471.    383.    316.    261.
BA    204.    148.    102.     61.     29.      9.      0.      0.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
BA      0.   1199.   1189.   1189.   1189.   1189.   1152.   1112.   1066.   1012.
BA    951.    885.    815.    751.    696.    640.    568.    487.    404.    304.
BA    194.    106.     59.     36.     25.     14.      7.      0.      0.      0.
BA      0.      0.      0.      0.      0.      0.      0.   1695.   1685.   1685.
BA   1685.   1685.   1645.   1599.   1547.   1492.   1435.   1378.   1326.   1280.
BA   1236.   1191.   1137.   1076.    998.    876.    709.    544.    419.    316.
BA    275.    202.    145.     98.     66.     43.     26.     12.      0.      0.
BA      0.      0.      0.   2552.   2552.   2552.   2552.   2552.   2502.   2445.
BA   2382.   2318.   2256.   2195.   2135.   2079.   2027.   1982.   1941.   1895.
BA   1835.   1743.   1595.   1403.   1196.    978.    942.    763.    594.    440.
BA    319.    222.    142.     77.     34.     17.      9.      0.      0.   3021.
BA   3018.   3018.   3018.   3018.   2957.   2893.   2826.   2761.   2701.   2640.
BA   2576.   2514.   2462.   2421.   2380.   2328.   2266.   2193.   2070.   1883.
BA   1654.   1428.   1428.   1214.    988.    771.    587.    430.    295.    179.
BA    100.     62.     36.      0.      0.   2587.   2468.   2363.   2363.   2363.
BA   2289.   2221.   2159.   2103.   2052.   2000.   1946.   1897.   1856.   1821.
BA   1781.   1726.   1661.   1592.   1490.   1346.   1184.   1071.   1071.    939.
BA    792.    645.    513.    396.    291.    193.    123.     85.     50.      0.
BA      0.   1932.   1761.   1574.   1445.   1394.   1288.   1203.   1142.   1097.
BA   1061.   1021.    974.    927.    882.    839.    794.    743.    694.    648.
BA    591.    524.    458.    421.    421.    376.    326.    275.    226.    182.
```

BA	140.	99.	68.	49.	30.	0.	0.	1810.	1605.	1393.
BA	1221.	1086.	901.	760.	672.	617.	577.	532.	470.	402.
BA	340.	291.	249.	213.	188.	169.	151.	133.	116.	107.
BA	107.	95.	83.	70.	58.	46.	36.	25.	18.	13.
BA	8.	0.	0.	1947.	1676.	1440.	1266.	1091.	844.	657.
BA	530.	441.	377.	319.	250.	181.	127.	94.	72.	56.
BA	47.	42.	38.	33.	29.	27.	27.	24.	21.	17.
BA	14.	12.	9.	6.	0.	0.	0.	0.	0.	1818.
BA	1467.	1210.	1054.	900.	685.	511.	367.	256.	185.	139.
BA	98.	61.	36.	24.	18.	14.	12.	11.	9.	8.
BA	7.	7.	7.	0.	0.	0.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	1380.	1055.	834.	702.	579.
BA	436.	312.	191.	103.	59.	38.	25.	15.	9.	6.
BA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BA	0.	868.	650.	493.	381.	279.	193.	131.	70.	31.
BA	15.	10.	6.	0.	0.	0.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	0.	0.	454.	307.	197.
BA	122.	72.	42.	27.	14.	6.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
BA	0.	0.	0.	0.	0.	0.	0.	0.		
75.	213.0	163.8	100.9	160.9	228.0	418.0				
75.	214.0	155.8	93.9	140.9	228.0	402.0				
75.	215.0	145.8	89.9	125.9	228.0	397.0				
75.	216.0	135.8	84.9	114.9	228.0	396.0				
75.	217.0	128.8	81.9	107.9	225.0	418.0				
75.	218.0	121.8	78.9	100.9	224.0	435.0				
75.	219.0	118.8	76.9	97.9	224.0	435.0				
75.	220.0	113.8	73.9	93.9	189.0	435.0				
75.	221.0	104.8	72.9	88.9	185.0	430.0				
75.	222.0	93.8	70.9	85.9	193.0	430.0				
75.	223.0	99.8	70.9	82.9	195.0	435.0				
75.	224.0	125.8	71.9	84.9	195.0	430.0				
75.	225.0	143.8	83.9	126.9	154.0	430.0				
75.	226.0	158.8	77.9	114.9	150.0	402.0				
75.	213.0	0.031	0.026	0.032						
75.	214.0	0.032	0.026	0.031						
75.	215.0	0.033	0.026	0.031						
75.	216.0	0.035	0.026	0.031						
75.	217.0	0.036	0.026	0.030						
75.	218.0	0.037	0.026	0.030						
75.	219.0	0.037	0.026	0.030						
75.	220.0	0.038	0.026	0.030						
75.	221.0	0.040	0.026	0.030						
75.	222.0	0.043	0.026	0.030						
75.	223.0	0.041	0.026	0.030						
75.	224.0	0.036	0.026	0.030						
75.	225.0	0.034	0.026	0.031						
75.	226.0	0.032	0.026	0.031						
75.	213.71	34.0	5.8	30.0	2158.1	75.2	72.1	49.4		
75.	214.09	29.0	0.0	0.0	0.0	46.0	23.2	49.3		
75.	214.34	40.0	0.0	0.0	1003.4	56.2	56.3	49.3		
75.	214.46	26.0	6.9	36.0	5933.0	95.8	98.3	49.4		
75.	214.59	24.0	9.2	32.0	6055.9	109.2	93.9	49.6		
75.	214.70	50.0	6.9	32.0	3789.7	107.4	86.7	49.7		

B4

75.	214.96	28.0	3.5	9.0	0.0	50.0	28.6	49.6
75.	215.09	26.0	3.5	14.0	0.0	49.3	21.6	49.6
75.	215.21	24.0	3.5	27.0	0.0	49.1	19.6	49.5
75.	215.33	28.0	0.0	0.0	3439.4	65.0	87.4	49.6
75.	215.46	25.0	8.1	32.0	6667.9	105.9	100.1	49.7
75.	215.58	26.0	5.8	29.0	6171.9	93.4	105.0	49.9
75.	215.72	24.0	4.6	33.0	2394.3	67.2	77.2	49.9
75.	215.84	[illegible]	0.0	0.0	0.0	47.7	38.3	49.9
75.	215.96	26.0	3.5	9.0	0.0	49.9	29.6	49.9
75.	216.08	25.0	0.0	0.0	0.0	45.7	23.6	49.9
75.	216.21	26.0	0.0	0.0	0.0	45.7	21.7	49.8
75.	216.34	33.0	2.3	27.0	3418.3	70.0	86.7	49.9
75.	216.46	34.0	3.5	28.0	6462.8	92.4	111.7	50.1
75.	216.59	28.0	4.6	33.0	5802.6	88.9	106.2	50.2
75.	216.71	28.0	6.9	34.0	2306.0	79.1	74.3	50.3
75.	216.96	24.0	0.0	0.0	0.0	46.1	30.0	50.2
75.	217.21	29.0	0.0	0.0	0.0	46.0	23.9	50.1
75.	217.34	33.0	0.0	0.0	3396.9	67.9	87.8	50.2
75.	217.46	47.0	3.5	33.0	6587.8	105.4	113.4	50.4
75.	217.58	36.0	4.6	32.0	4601.0	89.2	98.6	50.5
75.	217.71	31.0	2.3	34.0	1283.3	60.3	69.7	50.6
75.	218.21	33.0	3.5	36.0	0.0	50.5	27.2	50.4
75.	218.33	35.0	0.0	0.0	1895.4	61.1	72.6	50.5
75.	218.46	35.0	5.8	36.0	5443.1	96.8	100.0	50.6
75.	218.58	38.0	3.5	34.0	5022.7	88.8	103.3	50.7
75.	218.71	38.0	3.5	18.0	1271.5	65.1	67.0	50.8
75.	218.84	27.0	0.0	0.0	0.0	47.2	35.9	50.7
75.	218.96	36.0	0.0	0.0	0.0	48.4	34.1	50.7
75.	219.33	41.0	1.2	30.0	1874.0	65.1	73.5	50.8
75.	219.45	43.0	5.8	29.0	5214.8	103.0	98.7	51.0
75.	219.58	50.0	5.8	27.0	3671.8	101.6	90.2	51.1
75.	219.71	38.0	8.1	29.0	1898.7	90.6	69.8	51.1
75.	219.96	38.0	3.5	9.0	0.0	53.7	37.4	51.1
75.	220.21	36.0	0.0	0.0	0.0	47.6	29.7	51.0
75.	220.33	40.0	2.3	28.0	1733.8	64.7	70.1	51.1
75.	220.46	38.0	3.5	30.0	4899.4	87.6	101.8	51.2
75.	220.58	37.0	4.6	30.0	3993.5	86.0	93.5	51.3
75.	220.71	37.0	4.6	36.0	1247.3	68.7	67.1	51.3
75.	220.83	39.0	3.5	30.0	0.0	55.2	41.8	51.3
75.	221.09	38.0	3.5	31.0	0.0	52.1	31.0	51.3
75.	221.46	32.0	5.8	30.0	5398.0	94.7	100.6	51.7
75.	221.58	37.0	8.1	36.0	3980.4	103.6	85.8	51.8
75.	221.71	37.0	3.5	1.0	2045.0	68.4	74.1	51.8
75.	221.83	32.0	0.0	0.0	0.0	50.9	48.3	51.8
75.	221.96	35.0	2.3	33.0	0.0	49.8	33.3	51.8
75.	222.33	40.0	1.2	33.0	3259.2	72.0	86.5	52.0
75.	222.45	35.0	1.2	32.0	4333.5	77.4	100.0	52.1
75.	222.58	36.0	3.5	32.0	3319.2	77.4	89.8	52.2
75.	222.71	39.0	4.6	2.0	649.6	62.8	52.9	52.2
75.	222.84	38.0	2.3	9.0	0.0	51.9	39.2	52.2
75.	223.21	36.0	0.0	0.0	0.0	47.4	28.2	52.1
75.	223.33	38.0	0.0	0.0	2124.7	63.4	74.5	52.1
75.	223.45	56.0	4.6	34.0	2464.3	91.8	81.8	52.2
75.	223.59	41.0	9.2	34.0	2575.9	104.2	71.7	52.2
75.	223.71	36.0	6.9	31.0	642.8	73.8	57.2	52.3
75.	223.84	45.0	0.0	0.0	0.0	52.1	39.3	52.2
75.	223.96	45.0	2.3	18.0	0.0	53.4	37.5	52.2
75.	224.09	44.0	0.0	0.0	0.0	51.0	36.8	52.2
75.	224.21	37.0	2.3	18.0	0.0	49.3	28.9	52.2
75.	224.46	43.0	5.8	33.0	4240.8	95.3	90.3	52.4

75.	224.58	37.0	4.6	34.0	3620.1	82.3	88.5	52.4
75.	224.71	40.0	5.8	11.0	1065.9	70.1	57.2	52.5
75.	225.09	43.0	0.0	0.0	0.0	50.5	35.7	52.4
75.	225.21	44.0	2.3	27.0	0.0	52.6	35.7	52.4
75.	225.34	44.0	0.0	0.0	930.5	56.6	53.3	52.4
75.	225.46	42.0	0.0	0.0	2754.3	68.8	80.3	52.4
75.	225.58	42.0	8.1	33.0	1745.4	88.6	63.1	52.4
75.	225.71	40.0	11.5	31.0	2380.5	118.7	65.4	52.5
75.	225.84	42.0	1.2	36.0	0.0	50.6	35.4	52.5
75.	225.97	40.0	0.0	0.0	0.0	49.1	33.2	52.4
75.	226.08	36.0	0.0	0.0	0.0	47.4	28.2	52.4
75.	226.21	34.0	2.3	27.0	0.0	48.4	25.7	52.4
75.	226.33	34.0	1.2	36.0	1665.7	57.8	64.9	52.4
75.	226.45	37.0	4.6	33.0	4266.7	84.7	91.8	52.5
75.	226.58	41.0	3.5	20.0	1912.1	66.4	66.5	52.5
75.	226.71	37.0	11.5	33.0	1540.3	105.8	54.7	52.5

Appendix C

Example Output Data

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L A R M -- LATERALLY AVERAGED RESERVOIR MODEL

VERSION TWO -- MARCH 1981 -- WAYNE, PENNSYLVANIA

USER GUIDE EXAMPLE -- DILLON RESERVOIR, COLORADO -- 2/18/81
UPSTREAM INFLOW, TWO TRIBUTARIES, TWO WITHDRAWALS, AND NO OUTFLOW
ONE CONSTITUENT (AMMONIA)
IFORM=0 FOR SHORTENED AND COMPRESSED OUTPUT


CONTROL PARAMETERS

IMAX= 18  KMAX= 36  DLX=  552.75 M  HIN(1,1)= 2.00 M  DTM=2679.30 M
DLT=  900.00 S  NSTEPS=       48
IPLOT=0  M1=        0  M2=       48
IFORM=0  N1=        0  N2=       48
I0=   1   2   3   4   5   7   9  12  15
I1=   1   2   3   4   5   6   7   8   9  10
I1 (I2 CARD)=  11  12  13  14  15  16  17
TMSTRT=  214.50 DAYS  KT=  3  ZI= -1.2500 M  TI=10.50 C
NC=    1  ICC=    1 WITH INITIAL VALUES OF     .020
PHI0=     3.90 RAD  IEVAP=1
NOUT=     1 AT K=   10
NTRIB=     2 AT I=    9   17
NWD=    2 AT I=    9   10
      AND AT K=   28   35


INTERNALLY-SET PARAMETERS

AX= .1000E+01 M*M/S
AZMIN= .1500E-05 M*M/S
AZ0= .3000E-03 M*M/S
AZMAX= .1889E-02 M*M/S
BETA=    1.0000
CHZY=   70.0000 SQRT(M)/S
DXI= .1000E+01 M*M/S
DZMIN= .1400E-04 M*M/S
DZ0= .2800E-03 M*M/S
DZMAX= .1889E-02 M*M/S
GAMMA=      .4900 1/M
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LARM2 3/81 JES:  USER GUIDE EXAMPLE -- DILLON RESERVOIR, COLORADO -- 2/18/81

ELTM= 215.00000 DAYS (N=     48)  1975
QIN=     4.13 CMS  TIN=      9.8 C
QOUT (CMS)=      0.00
KOUT=              10
GET=      .35 CMS
QTRIB (CMS)=     2.55     3.57
TTRIB (C)=        9.8      9.8
ITRIB=              9       17
KTRIB=             35       10
QWD (CMS)=    6.46   11.24
IWD=              9       10
KWD=             28       35
CSHE=  .28E-05 M/S  SRO= 0.        (C M*M*M)/(S M*M)  ET=     -1.9 C
TD= -2.2 C  WA=  1.6 M/S  PHI= 1.57 RAD
RATIO OF SPACE TO TIME INTEGRATED VOLUME= 100.000 PER CENT

IL=     2  KT=     3  EL=2748.53 M
Z2 (M)
        1        2        3        4        5        7        9       12       15
  -1.2285-1.2285-1.2285-1.2284-1.2284-1.2283-1.2283-1.2282-1.2282
```

USER GUIDE EXAMPLE -- DILLON RESERVOIR, COLORADO -- 2/18/81
ELTM= 215.00000 DAYS

U (M/S)

	1	2	3	4	5	7	9	12	15
3	.0007	-.0037	-.0102	-.0200	-.0255	-.0173	-.0179	-.0192	-.0082
4	.0007	.0047	.0014	-.0052	-.0098	-.0031	-.0012	.0011	.0070
5	.0007	.0041	.0042	.0023	-.0004	.0011	.0014	.0054	.0094
6	.0007	.0011	.0039	.0053	.0043	.0020	.0017	.0061	.0088
7	.0007	-.0005	.0034	.0062	.0059	.0021	.0017	.0062	.0063
8	.0007	-.0003	.0034	.0064	.0063	.0021	.0017	.0062	-.0001
9	.0007	.0011	.0037	.0065	.0063	.0021	.0017	.0062	-.0113
10	.0007	.0033	.0042	.0065	.0063	.0021	.0017	.0062	-.0217
11	.0007	.0062	.0049	.0066	.0062	.0021	.0017	.0062	-.0241
12	.0007	.0081	.0051	.0066	.0062	.0021	.0017	.0062	-.0273
13	0.0000	0.0000	.0053	.0066	.0062	.0021	.0017	.0063	-.0296
14	0.0000	0.0000	.0057	.0067	.0062	.0021	.0017	.0064	0.0000
15	0.0000	0.0000	.0062	.0068	.0062	.0021	.0017	.0064	0.0000
16	0.0000	0.0000	0.0000	.0072	.0062	.0021	.0017	.0064	0.0000
17	0.0000	0.0000	0.0000	.0074	.0062	.0021	.0017	.0063	0.0000
18	0.0000	0.0000	0.0000	.0078	.0062	.0021	.0017	.0061	0.0000
19	0.0000	0.0000	0.0000	.0083	.0063	.0021	.0017	.0060	0.0000
20	0.0000	0.0000	0.0000	0.0000	.0066	.0020	.0017	.0059	0.0000
21	0.0000	0.0000	0.0000	0.0000	.0068	.0020	.0017	.0059	0.0000
22	0.0000	0.0000	0.0000	0.0000	.0087	.0020	.0017	.0058	0.0000
23	0.0000	0.0000	0.0000	0.0000	0.0000	.0020	.0017	.0058	0.0000
24	0.0000	0.0000	0.0000	0.0000	0.0000	.0020	.0017	.0058	0.0000
25	0.0000	0.0000	0.0000	0.0000	0.0000	.0020	.0017	.0057	0.0000
26	0.0000	0.0000	0.0000	0.0000	0.0000	.0020	.0017	.0056	0.0000
27	0.0000	0.0000	0.0000	0.0000	0.0000	.0021	.0017	.0056	0.0000
28	0.0000	0.0000	0.0000	0.0000	0.0000	.0020	.0018	.0056	0.0000
29	0.0000	0.0000	0.0000	0.0000	0.0000	.0019	.0017	.0055	0.0000
30	0.0000	0.0000	0.0000	0.0000	0.0000	.0019	.0017	.0054	0.0000
31	0.0000	0.0000	0.0000	0.0000	0.0000	.0020	.0017	.0052	0.0000
32	0.0000	0.0000	0.0000	0.0000	0.0000	.0018	.0017	.0044	0.0000
33	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0021	0.0000	0.0000
34	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0061	0.0000	0.0000
35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0226	0.0000	0.0000

USER GUIDE EXAMPLE -- DILLON RESERVOIR, COLORADO -- 2/18/81
ELTM= 215.00000 DAYS

W (MM/S)

	1	2	3	4	5	7	9	12	15
3	0.0000	.0349	.0468	.0617	.0424	.0127	.0143	-.0295	-.0515
4	0.0000	.0245	.0617	.0891	.0624	.0023	.0169	-.0422	-.0684
5	0.0000	.0121	.0628	.0969	.0720	-.0040	.0172	-.0535	-.0781
6	0.0000	.0126	.0585	.0951	.0756	-.0041	.0168	-.0664	-.0889
7	0.0000	.0280	.0554	.0927	.0778	-.0019	.0165	-.0815	-.1027
8	0.0000	.0530	.0534	.0900	.0793	.0007	.0163	-.0946	-.1141
9	0.0000	.0807	.0535	.0891	.0814	.0034	.0161	-.1035	-.1212
10	0.0000	.1011	.0575	.0920	.0846	.0060	.0159	-.1088	-.1265
11	0.0000	.0889	.0665	.0990	.0887	.0085	.0156	-.1129	-.1167
12	0.0000	0.0000	.0843	.1094	.0936	.0108	.0154	-.1194	-.0798
13	0.0000	0.0000	.0877	.1247	.0990	.0130	.0152	-.1296	-.0216
14	0.0000	0.0000	.0711	.1432	.1023	.0149	.0149	-.1418	-.0157
15	0.0000	0.0000	0.0000	.1610	.1016	.0166	.0146	-.1529	-.0089
16	0.0000	0.0000	0.0000	.1589	.1003	.0182	.0142	-.1618	0.0000
17	0.0000	0.0000	0.0000	.1489	.1014	.0196	.0139	-.1693	0.0000
18	0.0000	0.0000	0.0000	.1189	.1042	.0208	.0137	-.1728	0.0000
19	0.0000	0.0000	0.0000	0.0000	.1096	.0222	.0135	-.1704	0.0000
20	0.0000	0.0000	0.0000	0.0000	.1013	.0243	.0135	-.1654	0.0000
21	0.0000	0.0000	0.0000	0.0000	.0954	.0274	.0138	-.1611	0.0000
22	0.0000	0.0000	0.0000	0.0000	0.0000	.0302	.0146	-.1582	0.0000
23	0.0000	0.0000	0.0000	0.0000	0.0000	.0325	.0159	-.1518	0.0000
24	0.0000	0.0000	0.0000	0.0000	0.0000	.0330	.0161	-.1343	0.0000
25	0.0000	0.0000	0.0000	0.0000	0.0000	.0321	.0163	-.1170	0.0000
26	0.0000	0.0000	0.0000	0.0000	0.0000	.0350	.0181	-.1072	0.0000
27	0.0000	0.0000	0.0000	0.0000	0.0000	.0420	.0211	-.0990	0.0000
28	0.0000	0.0000	0.0000	0.0000	0.0000	.0388	.0083	-.0923	0.0000
29	0.0000	0.0000	0.0000	0.0000	0.0000	.0335	.0091	-.0872	0.0000
30	0.0000	0.0000	0.0000	0.0000	0.0000	.0259	.0104	-.0838	0.0000
31	0.0000	0.0000	0.0000	0.0000	0.0000	.0154	.0130	-.0848	0.0000
32	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0181	-.0907	0.0000
33	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0212	-.0842	0.0000
34	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-.0107	-.0637	0.0000

USER GUIDE EXAMPLE -- DILLON RESERVOIR, COLORADO -- 2/18/81
ELTM= 215.00000 DAYS

T2 (C)

	1	2	3	4	5	7	9	12	15
3	0.0	12.1	12.0	12.0	12.0	12.0	11.9	11.9	11.7
4	0.0	11.3	11.3	11.2	11.0	10.9	10.7	10.6	10.6
5	0.0	10.9	10.8	10.7	10.7	10.6	10.5	10.5	10.5
6	0.0	10.6	10.6	10.6	10.5	10.5	10.5	10.5	10.5
7	0.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
8	0.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
9	0.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
10	0.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
11	0.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
12	0.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
13	0.0	0.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5
14	0.0	0.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5
15	0.0	0.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5
16	0.0	0.0	0.0	10.5	10.5	10.5	10.5	10.5	10.5
17	0.0	0.0	0.0	10.5	10.5	10.5	10.5	10.5	0.0
18	0.0	0.0	0.0	10.5	10.5	10.5	10.5	10.5	0.0
19	0.0	0.0	0.0	10.5	10.5	10.5	10.5	10.5	0.0
20	0.0	0.0	0.0	0.0	10.5	10.5	10.5	10.5	0.0
21	0.0	0.0	0.0	0.0	10.5	10.5	10.5	10.5	0.0
22	0.0	0.0	0.0	0.0	10.5	10.5	10.5	10.5	0.0
23	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
24	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
25	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
26	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
27	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
28	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
29	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
30	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
31	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
32	0.0	0.0	0.0	0.0	0.0	10.5	10.5	10.5	0.0
33	0.0	0.0	0.0	0.0	0.0	0.0	10.5	10.5	0.0
34	0.0	0.0	0.0	0.0	0.0	0.0	10.3	10.5	0.0
35	0.0	0.0	0.0	0.0	0.0	0.0	9.9	10.5	0.0

USER GUIDE EXAMPLE -- DILLON RESERVOIR, COLORADO -- 2/18/81
ELTM= 215.00000 DAYS

C2 FOR CONSTITUENT 1

	1	2	3	4	5	7	9	12	15
3	0.000	.020	.020	.020	.020	.020	.020	.020	.020
4	0.000	.021	.020	.020	.020	.020	.020	.020	.020
5	0.000	.021	.020	.020	.020	.020	.020	.020	.020
6	0.000	.021	.020	.020	.020	.020	.020	.020	.020
7	0.000	.021	.020	.020	.020	.020	.020	.020	.020
8	0.000	.021	.020	.020	.020	.020	.020	.020	.020
9	0.000	.021	.020	.020	.020	.020	.020	.020	.020
10	0.000	.021	.020	.020	.020	.020	.020	.020	.021
11	0.000	.020	.020	.020	.020	.020	.020	.020	.021
12	0.000	.020	.020	.020	.020	.020	.020	.020	.021
13	0.000	0.000	.020	.020	.020	.020	.020	.020	.021
14	0.000	0.000	.020	.020	.020	.020	.020	.020	.020
15	0.000	0.000	.020	.020	.020	.020	.020	.020	.020
16	0.000	0.000	0.000	.020	.020	.020	.020	.020	.020
17	0.000	0.000	0.000	.020	.020	.020	.020	.020	0.000
18	0.000	0.000	0.000	.020	.020	.020	.020	.020	0.000
19	0.000	0.000	0.000	.020	.020	.020	.020	.020	0.000
20	0.000	0.000	0.000	0.000	.020	.020	.020	.020	0.000
21	0.000	0.000	0.000	0.000	.020	.020	.020	.020	0.000
22	0.000	0.000	0.000	0.000	.020	.020	.020	.020	0.000
23	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
24	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
25	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
26	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
27	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
28	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
29	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
30	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
31	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
32	0.000	0.000	0.000	0.000	0.000	.020	.020	.020	0.000
33	0.000	0.000	0.000	0.000	0.000	0.000	.020	.020	0.000
34	0.000	0.000	0.000	0.000	0.000	0.000	.021	.020	0.000
35	0.000	0.000	0.000	0.000	0.000	0.000	.025	.020	0.000

Appendix D

LARM2 Error Messages

GENERAL

LARM2 identifies two types of errors: (1) fatal errors which stop the computation; (2) non-fatal errors which permit the computation to continue. The messages written on the detection of these errors are discussed below.

FATAL INPUT ERROR

This error occurs when the input stream is missing a required card or the deck is out of order (see Appendix A). The code checks the card identifiers (field 0) and stops the computation when an error is detected. An input error also occurs when too few or too many outlets, tributaries, or withdrawals are specified. In both cases, LARM2 writes an error message, repeats the offending card, and stops the computation.

NON-FATAL ERROR: AZO EXCEEDS AZMAX

and

NON-FATAL ERROR: DZO EXCEEDS DZMAX

The variables AZO and DZO are set by the user and represent base values of vertical dispersion coefficients for the x-momentum and for temperature and constituent equations, respectively. These variables are used with the Richardson number to compute spatially and temporally varying dispersion coefficients. The upper limits on the latter, however, are values based on the horizontal layer thickness, h, and the time step Δt (see Appendix E). The values of AZO and DZO should always be less than these maximum values. This error is not serious enough to stop the computation, however, since the code always insures that the computed values of AZ and DZ do not exceed their computational limits.

FATAL COMPUTATION ERROR: VRATIO EXCEEDS ONE PER CENT DEVIATION LIMIT

This message indicates one of two conditions. Most frequently, a computational instability has occurred and the Δt needs to be decreased.

On very long simulations with short Δt's, this volume balance variable may deviate somewhat from its perfect value of exactly 100 due to roundoff error. This error does not affect the accuracy of the results. In cases where this roundoff error exceeds the one per cent limit by gradually increasing over time, the computation may be restarted part way through the simulation.

FATAL TVDS ERROR AT - DAYS

This error message is coded in the TVDS subroutine to detect the case where LARM2 asks for time-varying data that is not available if, for example, a simulation were set up for a 370-day run, with only one year of data available. The illegal time request is printed with the error message, and the computation is stopped.

Appendix E

LARM2 Glossary of Important FORTRAN Variables

The glossary lists only those FORTRAN variables found on the LARM2 printed output, in the FORTRAN statements labelled CHANGE, in the TVDS arguments, and in this report. Those variables discussed in the card description Appendix A are not repeated here.

A: vector containing subdiagonal (backward) coefficients for the tridiagonal algorithm solutions of Z, T, and C

AR: waterbody area by layer, m^2 (vector)

AS: A Storage: array for storing A vectors for use in constituent concentration computations

AX: A_x, m^2/s; x-direction momentum dispersion coefficient

AZ: A_z, m^2/s; dispersion coefficient, z-direction, x-momentum equation (array)

AZMAX: maximum permitted value of A_z $(0.85 \cdot \frac{1}{2} \cdot h^2/\Delta t)$, m^2/s

AZMIN: minimum value of A_z (molecular value), m^2/s (scalar)

AZO: base value for A_z computation, m^2/s (scalar)

B: B, m, cell width (array)

BETA: β, fraction of incident solar radiation absorbed at the water surface

BH1: $B \cdot h$, m^2, cross-sectional area of a cell at the current or previous time step

BH2: $B \cdot h$, m^2, cross-sectional area of a cell at the previous or current time step

C: vector containing superdiagonal (forward) coefficients for the tridiagonal algorithm solution of Z and T

CHZY: Chezy resistance coefficient, $m^{\frac{1}{2}}/s$

CIN: upstream inflow constituent concentration, $mg \cdot l^{-1}$ (vector)

CS: C Storage: array for storing C vectors for use in constituent concentration computations

CSHE: k, kinematic coefficient of surface heat exchange, $m \cdot s^{-1}$

CTRIB: array containing tributary constituent concentrations, $mg \cdot l^{-1}$

CZ: C*, wind resistance coefficient; varies with wind speed

C1: array containing constituent concentrations at the current or previous time step, $mg \cdot l^{-1}$

C2: array containing constituent concentrations at the current or previous time step, $mg \cdot l^{-1}$

D: vector containing right-hand side for the tridiagonal algorithm solution of Z and T

DX: D_x, m^2/s; dispersion coefficient, x-direction, heat and constituent balance equation (array)

DXI: base value of D_x, m^2/s (scalar)

DZ: D_z, m^2/s; dispersion coefficient, z-direction, heat and constituent balance equation (array)

DZMAX: maximum permitted value of D_z $(0.85 \cdot \frac{1}{2} \cdot h^2/\Delta t)$, m^2/s (scalar)

DZMIN: minimum value of D_z (molecular value), m^2/s (scalar)

DZO: base value of D_z computation, m^2/s (scalar)

EL: water surface elevation, m

ELTM: elapsed time, days; sum of $N\Delta t$ and TMSTRT; time since beginning of calendar year

ET: E, equilibrium temperature of surface heat exchange, $^{\circ}C$

G: g, m/s^2; gravitational constant

GAMMA: γ, m^{-1}; exponential decay constant for absorption of solar radiation with depth

HIN: H Initial, m; retains original value of h (layer thickness) for computation of varying h in top layer of cells from Z and also used in reinitializing a layer of cells immediately after a layer has been added or subtracted due to reservoir volume changes

HN: H_n, $^{\circ}C \cdot m^3 s^{-1}$ or $mg \cdot l^{-1} m^3 s^{-1}$; net rate of heat or constituent addition; source term for heat balance or constituent equation

H1: h, m; vertical slice thickness at the current or previous time step. (Only the top layer of cells has varying thickness due to elevation changes, however, the location of the top layer of cells may vary due to extreme elevation changes)

H2: h, m; vertical slice thickness at the current or previous time step

I: counter for sweeping across (longitudinally) the reservoir grid in x-direction DO-loops

IB: I Begin: variable locating the first active cell in each line for use in the tridiagonal solution of the heat balance equation; IB is found in an initial program step and stored in the array LC

IE: I End: variable locating the last active cell in each line for use in the tridiagonal solution of the heat balance equation; IE is found in an initial program step and stored in the array LC

IFLAG: logic flag for subroutine TVDS; if IFLAG=0; instruct TVDS to read time-varying boundary condition data; if IFLAG=1, instruct TVDS to provide boundary condition data for a particular time; if IFLAG=-1, TVDS error and computation stopped

IFORM: control variable; if IFORM=0, terminal-oriented display is produced (80-character width); if IFORM=1, full-width (132-character) display is produced

IL: I Left: I-index of current left-hand segment

IMAX: I MAXimum: I-index of the rightmost segment

IMAXM1: I MAXimum Minus 1: I-index of the next-to-rightmost segment

IMAXM2: I MAXimum Minus 2: I-index of the second-to-rightmost segment

ISC: Integer Segment Coordinates: vector containing K-index of bottom active cell of each segment

IY: Integer Year: year number

JC: constituent counter

K: counter for sweeping down (vertically) the reservoir grid in z-direction DO-loops

KB: K Bottom: K-index of bottom active cell in a particular segment; KB is found in array ISC

KMAX: K-MAXimum: K-index of the bottom layer of cells

KMAXM1: K-MAXimum Minus 1: K-index of the next-to-bottom layer of cells

KOUT: computed layer number at which each tributary enters the LARM2 grid (vector)

KT: K-Top: K-index of the currently active top layer of cells

L: integer variable denoting active cells (L-1) or inactive cells (L=0)

LC: Layer Coordinates: array containing (1) layer number (K), (2) IB, and (3) IE for each active layer of cells

N: counter for time steps

P: pressure, Pa

PHI: ϕ, degrees; wind direction

QET: Q Evaporation Total, m^3/s; evaporation rate

QIN: upstream inflow rate, $m^3 \cdot s^{-1}$

QOUT: vector containing downstream outflow rates

QTRIB: Q TRIButary, m^3/s; vector containing tributary inflow rates

QWD: Q WithDrawal, m^3/s; vector containing withdrawal rates

RHO: ρ, kg/m^3; density of water

RHOA: ρ_a, kg/m^3; density of air (used in wind stress computation and assumed constant at 1.25 kg/m^3)

RR: constituent reaction rate, s^{-1}

SRO: solar radiation, $(^{o}C \cdot m^3/s)/m^2$

T: vector containing the results of the layer-by-layer solution of the implicit temperature equation

TAPE5: read device

TAPE6: write device

TAPE61: binary write device

TD: T_d, ^{o}C: dew point temperature

TIN: upstream inflow temperature, ^{o}C

TMSTRT: time of year in Julian days when simulation starts; read in as days, converted internally to seconds

TTRIB: Temperature of TRIButary, ^{o}C; vector containing tributary temperatures

T1: T, ^{o}C; array containing temperatures at the current or previous time step

T2: T, ^{o}C; array containing temperatures at the previous or current time step

U: U, m/s; array containing x-direction velocity components

UM: cell average x-direction velocity, m s^{-1}

V: vector containing main diagonal (centered) coefficients for the tridiagonal algorithm solution of Z and T

VOL: reservoir volume, m^3; based on initial volume and sum of inflows and outflows

VOLE: cumulative waterbody volume by layer, m^3 (vector)

VOLP: reservoir volume, m^3; computed from geometry and water surface elevations

VRATIO: ratio of VOLP to VOL, %

VS: V Storage: array for storing V vectors for use in constituent concentration computations

W: W_b, m/s; array containing vertical velocities

WA: w_a, m/s; wind speed

WKT: a vector containing a corrected vertical velocity for the top layer of cells that permits a perfect water balance in that layer

WM: cell average z-direction velocity m s^{-1}

Z1: Z, m; vector containing deviation of water surface from datum (top of active layer of cells) for each column; positive downwards. The "1" denotes a particular time level

Z2: Z, m; vector containing deviation of water surface from datum (top of active layer of cells) for each column; positive downwards. The "2" denotes a particular time level

Appendix F

Preprocessor GIN

GIN is a preprocessor code that prepares bathymetry (BA) cards for use by LARM2. GIN uses GEDA output as input and may be used to preview the grid geometry prior to creating the BA cards. The code is short and is documented internally with comment cards. Following are the most important features of GIN.

- The basis grid parameters, Δx and h, are selected during the GEDA run. Output from the final GEDA run is modified by eliminating all output lines preceding "GEOMETRIC MODEL FOR UNSTEADY FLOW PROGRAMS." This modified GEDA output is the only input to GIN.
- The variable IFORM can be set to 0 or 1 in line 27 of GIN. If IFORM=0, the grid geometry is previewed in a form similar to that presented by LARM2. If IFORM=1, the BA cards are written. The user will generally run GIN with IFORM=0 until a satisfactory grid is established, then with IFORM=1 as a final step before working with LARM2.
- The segment order may be reversed by changing the variable IMAGE.
- GIN may be used to modify a grid geometry by changing some lines of the code. The example for Dillon Reservoir shows some lines marked "CHANGE" in columns 73-80 in DO-loop 170 that modify widths to fit better the given elevation-area-volume table. The best compromise in fitting such tables may be to match areas in the surface layers and volumes elsewhere.
- The user is responsible for obtaining a legal geometry as outlined in Section 4.2 of this report.
- GIN uses GEDA output in feet and converts all dimensions to metres.

Appendix G

Postprocessor VV

VV is a postprocessor code that uses the velocity fields generated by LARM2 to produce vector plots like that shown on page G3. VV uses DISSPLA, a proprietary software package created by Integrated Software Systems Corporation of San Diego and available on many time-sharing systems. VV uses a file created by LARM2 when the IPLOT parameter on the PL card is set to one. The code is short and documented internally with comment cards. However, familiarity with DISSPLA subroutines is required to use VV. Following are some of the most important features of VV.

- LARM2 writes the contents of the TITLE and GE cards to TAPE61 in binary prior to writing the coordinates of all the LARM2 cells and the velocity fields. VV reads this information on TAPE51.

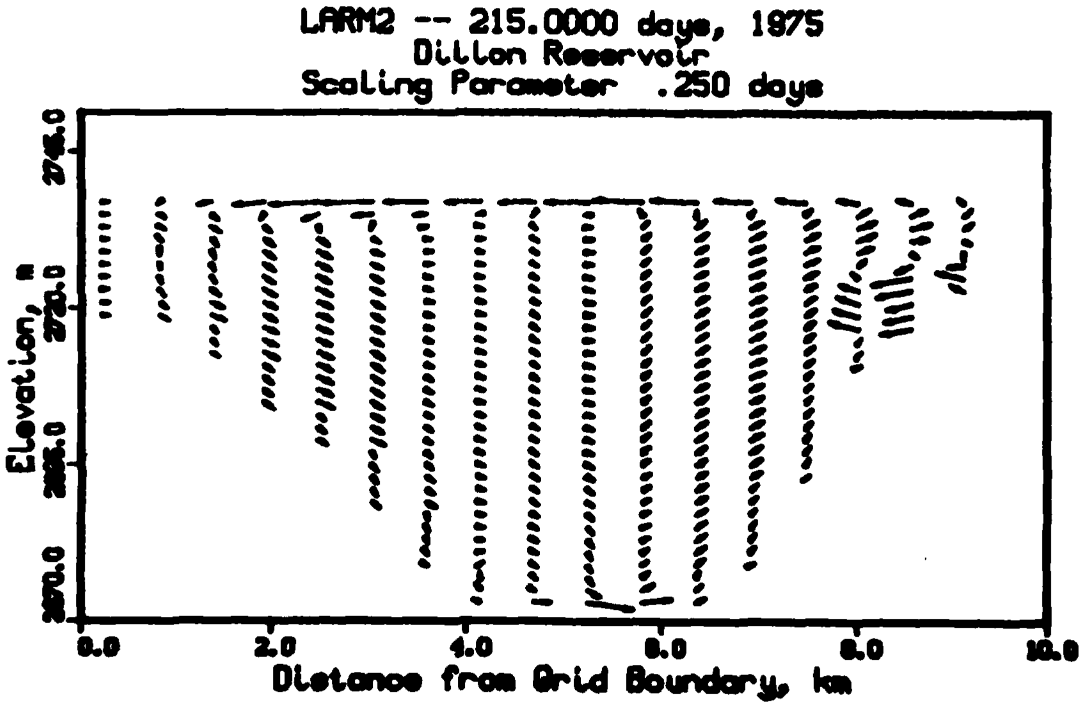
- VV computes all the scaling parameters and axis labels from information written by LARM2. The user can change the axis sizes and location of the plot on the paper by changing the values of XAXIS, ZAXIS, XSTART, and ZSTART (all in inches).

- The velocity components are translated to a displacement from the cell center by multiplying each component by DLT, a time in seconds. Different applications yield different velocity magnitudes, so the user may need to change the value of DLT. It is converted to days and identified as the scaling parameter on each plot.

- The velocity components used by VV are averaged to the cell center so that $\bar{U}(I,K) = (U(I-1,K) + U(I,K))/2$ and $\bar{W} = (W(I,K-1) + W(I,K))/2$. This averaging process may result in stepped velocity profiles adjacent to vertical boundaries.

- The user may select the number of velocity plots by manipulating the PSTART and PEND parameters.

- VV also writes all the plot definition variables and title information to TAPE6 as a debugging aid.



Appendix H

List of LARM Application Reports

Hydrodynamics and Transport of Chlorine in Panther Branch Arm, Squaw Creek Reservoir for Commanche Peake S.E.S., John Eric Edinger and Edward M. Buchak, prepared for Texas Utilities Services, Inc., Dallas, Tex., June 1978.

A Hydrodynamic, Two-Dimensional Reservoir Model: Development and Test Application to Sutton Reservoir Elk River, West Virginia John Eric Edinger and Edward M. Buchak, prepared for U. S. Army Engineer Division, Ohio River, Cincinnati, June 1979.

Temperature and Hydrodynamic Predictions for Center Hill Lake Using the LARM Two-Dimensional Computer Model, John A. Gordon, prepared for U. S. Army Engineer District, Nashville, June 1979.

A Review of Numerical Reservoir Hydrodynamic Modeling, Billy H. Johnson, Technical Report E-81-2, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., November 1981.

Hydrothermal Simulations of Commanche Peake Safe Shutdown Impoundment, Edward M. Buchak and John Eric Edinger, prepared for Texas Utilities Services, Inc., Dallas, Tex., May 1980.

"An Evaluation of the LARM Two-Dimensional Model for Water Quality Management Purposes," John A. Gordon, published in Proceedings of the Symposium on Surface-Water Impoundments held in June 1980, Minneapolis, Minn., by the American Society of Civil Engineers.

Thermal Demonstration Pursuant to Illinois Pollution Control Board Rules and Regulations Chapter 3, Rule 203(i)(10), Energy Impact Associates, prepared for Illinois Power Company, Decator, Ill., July 1980.

Development Document Relating to the 1979 Temperature Simulation Studies Battle River Reservoir Phase 1, MacLaren Engineers Planners and Scientists, Inc., and J.E. Edinger Associates, Inc., prepared for Alberta Power Limited, Edmonton, Alberta, Canada, October 1980.

Estuarine Laterally Averaged Numerical Dynamics: The Development and Testing of Estuarine Boundary Conditions in the LARM Code, John Eric Edinger and Edward M. Buchak, prepared for U. S. Army Engineer District, Savannah, July 1980.

Un-ionized Ammonia Distribution in Blue River Arm of Dillon Reservoir, J.E. Edinger Associates, Inc., and Black & Veatch, Kansas City, Kans., March 1981.

Appendix I

Julian Date Calendar

JULIAN DATE CALENDAR

Day	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Day
1	001	032	060	091	121	152	182	213	244	274	305	335	1
2	002	033	061	092	122	153	183	214	245	275	306	336	2
3	003	034	062	093	123	154	184	215	246	276	307	337	3
4	004	035	063	094	124	155	185	216	247	277	308	338	4
5	005	036	064	095	125	156	186	217	248	278	309	339	5
6	006	037	065	096	126	157	187	218	249	279	310	340	6
7	007	038	066	097	127	158	188	219	250	280	311	341	7
8	008	039	067	098	128	159	189	220	251	281	312	342	8
9	009	040	068	099	129	160	190	221	252	282	313	343	9
10	010	041	069	100	130	161	191	222	253	283	314	344	10
11	011	042	070	101	131	162	192	223	254	284	315	345	11
12	012	043	071	102	132	163	193	224	255	285	316	346	12
13	013	044	072	103	133	164	194	225	256	286	317	347	13
14	014	045	073	104	134	165	195	226	257	287	318	348	14
15	015	046	074	105	135	166	196	227	258	288	319	349	15
16	016	047	075	106	136	167	197	228	259	289	320	350	16
17	017	048	076	107	137	168	198	229	260	290	321	351	17
18	018	049	077	108	138	169	199	230	261	291	322	352	18
19	019	050	078	109	139	170	200	231	262	292	323	353	19
20	020	051	079	110	140	171	201	232	263	293	324	354	20
21	021	052	080	111	141	172	202	233	264	294	325	355	21
22	022	053	081	112	142	173	203	234	265	295	326	356	22
23	023	054	082	113	143	174	204	235	266	296	327	357	23
24	024	055	083	114	144	175	205	236	267	297	328	358	24
25	025	056	084	115	145	176	206	237	268	298	329	359	25
26	026	057	085	116	146	177	207	238	269	299	330	360	26
27	027	058	086	117	147	178	208	239	270	300	331	361	27
28	028	059	087	118	148	179	209	240	271	301	332	362	28
29	029		088	119	149	180	210	241	272	302	333	363	29
30	030		089	120	150	181	211	242	273	303	334	364	30
31	031		090		151		212	243		304		365	31

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